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THE STATUS OF V/STOL AIRCRAFT TECHNOLOGY

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FOREWORD

The report that follows is the result of a unique educational experience and much hard work on the part of nine Aerospace Engineering graduate students. The young men involved were provided with academic resources, permission to make long distance telephone calls, a budget for travel, report reproduction and photographic services and the pertinent subject of V/STOL aviation. They were free to proceed in any manner to investigate the topic, subject only to the time limitations imposed by a single academic quarter and the requirement that they present their findings in both oral and written form.

This type of educational experience has been referred to as "student-centered teaching" or "self-initiated learning" by the eminent psychologist Carl Rogers. Dr. Rogers summarizes the aims of this approach in the following way:*

> "The goal ... is to assist students to become individuals who are able to take self-initiated action and to be responsible for those actions; who are capable of intelligent choice and self-direction; who are critical learners, able to evaluate the contributions made by others; who have acquired knowledge relevant to the solution of problems; who, even more importantly, are able to adapt flexibly and intelligently to new problem situations; who have internalized an adaptive mode of approach to problems, utilizing all pertinent experience freely and creatively; who are able to cooperate effectively with others in these various activities; who work, not for approval of others, but in terms of their own socialized purposes."

I feel that many of these aims have been accomplished, and I never cease to be amazed at the growth, self-esteem and resourcefulness that emerge in such a context. In fact, this activity should not be evaluated on the basis of the knowledge or satisfaction gained but upon what the participants become in the process.

I am grateful to the National Science Foundation and the Georgia Institute of Technology for supporting this work. Also, the cooperation of Dr. Arnold L. Ducoffe, Director of the School of Aerospace Engineering, is sincerely appreciated.

Lawrence W. Rehfield
Associate Professor, G.I.T.

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* Rogers, Carl R., "Learning to be Free," Person to Person: The Problem of Being Human, edited by Carl Rogers and Barry Stevens, Real People Press, Lafayette, California, 1967, pp. 47-66.

ABSTRACT

The current status of V/STOL aircraft technology has been surveyed in an attempt to identify the general state of the art of this type aircraft.

In addition, the report identifies the various V/STOL concepts with a brief discussion on their general method of operation. For each of these concept areas, a historical sketch, current status, and future research is presented. The areas presented are; High Lift Wing Devices, including internally-externally blown flaps, augmentor-wings, and boundary layer control; Turbine Engine Vectored Thrust Concepts, including fans, ducts, and thrusters; Mechanical Vectored Thrust Concepts, including tilt wing, tilt engines and props; and Compound Vehicles. The pure helicopter is not considered in this report.

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Also, the cooperation of the following companies, governmental agencies, and schools without whose help this project would not have been possible, is sincerely appreciated:

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U. S. Army Air Mobility R & D Laboratory
U. S. Aviation Systems Command
U. S. Naval Test Pilot School

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CHAPTER I

INTRODUCTION

The purpose of the project from which this report was derived was to accomplish the following:

(1) Report on the state of the art of V/STOL aircraft technology.

(2) Analyze future research and development requirements.

(3) Create an unique educational experience for those students participating in the project.

This report includes an investigation of the past, present, and future technological state of the art of both military and commercial VTOL and STOL hardware and concepts. Although the main emphasis was placed on the technological area, other aspects, such as economic and environmental were investigated and included in those cases in which the results were directly attributed or related to problems, conclusions, decisions, and/or concepts pertaining to that particular aspect.

The boundaries of the investigation from past through future included as a beginning, that period in which the advent of the helicopter became a necessary requirement for military usage and essentially an economic feasible mode of transportation for commercial usage (chronologically around 1960). The future includes untested concepts presently in the "drawing board" stage and beyond.

The primary means of achieving V/STOL capabilities falls under the following general categories:

High Lift Wing Devices
Vectored Thrust
Rotors (Pure and Compound)
External Assist

This report investigates the first three areas above with the exception of the pure helicopter. The pure helicopter is not considered on the grounds that it has a state of the art well established and in no way implies any conclusions on the part of the authors. The external assist area, thought by some to be an answer in achieving V/STOL capabilities, is not considered since there has been no serious exploration in this area, other than military.

In each chapter the V/STOL concept presented contains a brief discussion on the general method of operation of that concept in addition to reporting on the status.

In investigating the various concepts, a need existed to understand to some degree the general economic and regulation problems encountered with V/STOL operation. A summary of areas investigated is included in the appendices of the report.

CHAPTER II

HIGH LIFT WING DEVICES

General

It is a basic fact of aerodynamics that there is a minimum speed at which a given wing will support flight. This speed is known as the stalling speed of the wing. It is the speed at which the angle of attack required to produce a specified lift is such as to result in extensive flow separation from the wing. It is at this speed, or very close to it, that the maximum lift coefficient of the wing is realized.

To see how these facts influence our discussion, consider the basic equation for the lift of a finite wing:

$$L = \frac{1}{2} \rho V^2 S C_L$$

where

L = Lift

ρ = Air Density

V = Velocity

S = Wing Area

C_L = Wing Lift Coefficient

Rearranging the equation, we consider the case of level, unaccelerated flight for which $L = W =$ WEIGHT OF AIRPLANE, and:

$$\left(V_{STALL}\right)_{MIN} = \left[\frac{2W}{\rho \; C_{L_{Max}} \; S}\right]^{\frac{1}{2}}$$

It is evident that for a given aircraft weight, increasing either $C_{L_{MAX}}$ and/or S will decrease V_S.

V_S is of interest not only because it represents a lower limit of airspeed at which wing supported flight is possible, but because it directly influences approach and departure speeds.

To provide a margin of safety for gust conditions, maneuvering acceleration, and engine failure, approach speeds of approximately 1.2 to 1.3 the stall speed are used. The higher the approach/departure speeds, of course, the longer will be the runway required. Figure 1 shows approach speed and landing field lengths vs. aircraft wing loading and lines of constant approach lift coefficient [1].

One solution to reduce V_S is to use a low wing loading, i.e., "large S," in conjunction with an airfoil section producing a relatively high $C_{L_{MAX}}$ in its basic form.

Equipping such an aircraft with moderately powerful flaps and a high power to weight ratio will result in the typical smaller "STOL" aircraft which have been in operation for some time in "bush country" and unimproved area service.

The main drawbacks to this approach are low efficiency at cruise, low cruising speed, and poor ride quality due to gust sensitivity.

Another approach is to size the basic wing area for high speed cruise efficiency, select a good high speed low drag airfoil shape, and strive to obtain very high C_L values by means of stowable high lift devices to be used during low speed flight only.

This can result in wing loadings on the order of 60-100 lbs/ft^2 which provides ride qualities comparable to present jet transports [2].

This approach has in a limited sense been used by the designers of present transport aircraft. Some of these can achieve $C_{L_{MAX}}$ values on the order of 2.7 to 3.0, through the use of mechanical triple-slotted fowler flaps and leading edge flaps and/or slats. Usable approach lift coefficients, however, come within the range of no more than 1.5 to 1.8, resulting in approach speeds of 95 to 160 knots. Thus, it can be seen that mechanical high lift devices alone do not guarantee the achievement of STOL performance when coupled with a highly loaded wing.

The following design concepts to produce high C_L values from a highly-loaded wing will be discussed here:

(1) Deflected slipstream
(2) Externally blown flap
(3) Internally blown flap
(4) Augmentor-wing
(5) Direct boundary layer control
(6) Rotating cylinder flap
(7) Lateral (spanwise) blowing

Although these concepts differ in their mechanical arrangement, they all have one thing in common. They use power to energize the airflow over the wing/flap combination in order to delay flow separation.

Deflected Slipstream

In the deflected slipstream concept (Figure 2) the wing is normally equipped with large chord double or triple slotted fowler flaps and leading edge slats and/or flaps. The maximum possible amount of the wing/flap system are immersed in the powerplant slipstream. Only turboprop engines have been employed in this concept due to the large airflow capture area of the propellers and the cool nature of the slipstream.

Since the propeller slipstream is moving at velocities greater than those of the free air stream, the wing/flap system responds as though it were moving at greater forward velocities, i.e., the resultant airflow has higher total energy.

This allows the use of larger chord flaps and larger flap deflection angles without flow separation at low forward speeds on the airplane. These large chord flaps in turn deflect the slipstream downward resulting in high values of circulation about the wing/flap system. Considerable direct lift may be developed in this manner with zero vehicle forward velocity.

Among aircraft employing this concept are the proposed De Havilland of Canada DHC-7 [3], the Brequet 941/McDonnell Douglas 188, the Japanese Shin Meiwa PS-1, the proposed Brazilian MB-500 Amazonas and Australian Government Factories Project N22 Aircraft [4].

The Brequet 941/McDonnell Douglas 188 (Figure 3) incorporates an elaborate engine/propeller cross-shafting system to minimize engine-out effects at low airspeeds. In addition, lateral and directional control are aided by the availability of $\pm 4.5^{\circ}$ of differential pitch from the outboard propellers with flaps in the deflected slipstream configuration.

The cross shaft system interconnecting the four propellers and power turbines results in one engine-out operation with no loss of control, with 83% thrust remaining available. One and two engine-out take off and landing operations have shown the aircraft to retain the handling characteristics available during normal flight.

The cross-shaft system consists of four small diameter, high RPM (UP TO 6000 RPM, TAKEOFF), steel shafts connecting the four angle gearboxes located behind each of the engines. These shafts are mounted in supports on the front spar of the wing.

The cross-shaft system is essentially unloaded except for torque induced through use of the outboard propeller differential pitch or during failure of an engine or drive train component.

The system provides several safety features:

(1) In the event of an engine or engine gear failure, an overrunning clutch isolates the engine from the rest of the system. Then the cross-shaft drives the propeller.

(2) If the propeller or prop gear box fails, a clutch actuated from the cockpit isolates propeller and gearbox, and feathers the propeller. Power from the associated engine is then available to the cross shaft for redistribution to other propellers.

(3) In case of an angle gear failure, a shear neck fuse breaks from overload and the entire nacelle is isolated [5].

An advanced version of this airplane, the McDonnel Douglas 188F is under consideration by American Airlines as an interim STOL aircraft for operation over the carrier's short-haul routes. The aircraft would carry 63 passengers and meet American's 1800 foot field length requirement. It would be powered by four G.E. CT58-16 engines rated at 1600 shp at 90°F at S.L. [6].

The Japanese Shin Meiwa PS-1 flying boat (Figure 4) employs both the deflected slipstream concept and internally blown flaps to achieve lift coefficients greater than seven.

Over 50% of the total lift in the STOL configuration is due to the deflected slipstream (Figure 5). As may be seen, about one half of the total lift at the take off results from the deflected slipstream, while about 35% is basic lift and the other 15% is attributable to flap blowing. The flap blowing details are discussed under INTERNALLY BLOWN FLAPS.

The outer portions of the wing and the entire span of the horizontal stabilizer are fitted with leading edge slats. These slats are actuated by dynamic pressure in the cruise regime and are hydraulically extended in STOL operation (flaps below 40°). The slats on the stabilizer are inverted to prevent lower surface separation due to the strong downwash of the wing/flap combination, shown in Figure 6.

The aircraft employs conventional rudder, elevators, ailerons, and spoilers. In the STOL configuration the rudder, aileron, and elevator travel are increased by a gear change mechanism and the outer flap panels act as additional aileron surfaces. Aerodynamic control effectiveness is enhanced by boundary layer control air which is blown over the lower surface of the elevators and both sides of the rudder. The air is supplied by the same system which blows the flaps. Flap deflections for take-off are $60°/45°$ (inboard/outboard) and for landing are $80°/60°$ (inboard/outboard).

The STOL configuration C_L is said to be substantially constant above angles of attack of $15°$ falling off gradually at about $\alpha = 30°$. There are no abrupt moment changes or loss of control effectiveness. However, as α increases, there is a rapid increase of C_D which results in considerable rate of sink.

The aircraft is capable of operation at gross weights up to 99,000 pounds and at speeds down to 45 knots. Representative actual landing and take off data are shown in Figures 7 and 8. Estimated land plane mode take off and landing data are shown in Figure 9. Payload vs. Range of a projected commercial amphibian are depicted in Figure 10, for two take off weights and cruise speeds of 260 and 290 knots [7].

A land-plane derivative of this airplane, the Grumman Model 487C, is under consideration by American Airlines at this time. This airplane uses the basic wing, empenage and powerplants of the PS-1, but Grumman has designed two new fuselages for it. The commercial version can accommodate up to 90 passengers [6].

It has been shown that aircraft using the deflected slipstream concept can provide good STOL performance. Several full scale prototypes exist and have been flying for some time. Low speed control and engine out problems appear to be surmountable with proper design. Furthermore, deflected slipstream aircraft appear to offer relatively low noise level operation. However, their cruise speeds are not in the present day jet transport class. Their propellers may also limit acceptance by a jet-conscious public.

Externally Blown Flap

In the externally blown flap concept, shown schematically in Figure 11, the exhaust from high bypass ratio turbofan engines is directed onto large chord multiple-slotted flaps which are deflected to large angles.

This concept was first proposed by John Campbell of the NASA Langley Research Center in the mid 1950's [1]. It strives to avoid the complexities and weight of the ducting attendant to internally blown flaps. Also, the entire exhaust flow of the engine is brought into play to generate lift. Unfortunately, at the time of the concept's inception, the only engines available were turbojetjets or low-bypass turbofans which would have placed the flaps in a very high temperature/velocity environment. Thus the designers of that time strived to avoid any exhaust impingement on the flap system and the concept lay dormant for nearly a decade.

The advent of the high bypass ratio turbofan, however, has reawakened interest in the externally blown flap. These engines deliver large quantities of cooler, lower velocity air than previously attainable. They also permit sizing of the engines for take off lift requirements without undue efficiency losses at part-throttle cruise operation.

High lift is produced partially by the downward deflection of the engine exhaust. In addition, the flow tends to spread outward to cover most of the flap span, causing supercirculation of the airflow. The resulting jet sheet tends to act as an extension of the physical flap itself. Moreover, some of the induced flow passes through the slots in the flap system to energize the boundary layer and hence prevent flow separation behind the flap. Figure 12 shows a recent model in the wind tunnel at Langley. The smoke flow shows the high downwash attained well outboard of the engines, indicating high lift [1].

The possibility of engine failure during STOL operation represents an obvious concern, since the engines are playing a large role in lift development. An engine-out condition thus results in asymmetric loss of lift and high rolling moments. These rolling moments may be minimized, but not eliminated, by installing the engines close inboard.

Since an engine failure also causes a reduction in overall lift, it is desirable to devise a control system capable of trimming out the asymetry of a failed engine with no further loss of lift. One method of achieving this is to use differential flap deflection for roll control in an engine-out condition - i.e., the flap on the side of the failed engine is lowered further, while the flap on the side with all engines operating is raised slightly. Another approach would be to cross duct bleed air from the engines to the opposite aileron for boundary layer control. An engine failure would then automatically direct twice as much bleed air to the aileron lowered to counteract roll.

Figure 13 shows typical data for the landing approach aerodynamics of a four engine blown flap configuration for a flap deflection of 50°. Here positive values of longitudinal force coefficient indicate excess drag and correspond to a descent condition. Negative values indicate excess thrust, and hence climb or acceleration conditions. The typical approach operating point (Point A) represents a 5° descending flight path ($\gamma = 5^\circ$), a margin from stall of 10° in angle of attack and 20% in speed from three-engine at-maximum-thrust stall speed. If the approach must be aborted with an engine out, application of full power on the remaining three engines shifts the operating point to B, i.e., zero sink. A 10° flap retraction then shifts the operating point to C, providing the needed rate of climb [1].

Aerodynamic and flying characteristics of externally blown-flap aircraft are presently being investigated in depth by NASA at Langley and at the Ames Flight Research Center. Figure 14 shows a dynamically scaled model which is being prepared for free-flight investigations of the stability and control characteristics of the concept.

A problem which will be encountered by externally blown flap aircraft designs is high noise levels. Figure 15 indicates that engine pressure ratio will play a major role in the noise reductions possible.

With proper application of low-noise level design techniques and accoustical treatment to suppress fan noise, the predominant noise source of current high bypass ratio turbofans becomes the jet mixing noise of the core and fan exhaust flows. Impingement of the flow on the flap system further increases the noise level. Dropping the present 1.5 pressure ratios to about 1.2 can be seen to significantly reduce these noise levels. This corresponds to approximately doubling the bypass ratio and increasing the nacelle diameter by about 25%.

To date there is no flight experience with an aircraft employing an externally blown flap system. However, NASA Flight Research Center has been developing a program to obtain such an aircraft.

France's Societe Bertin & Cie. has designed a STOL feederliner employing the externally blown flap concept. The aircraft is called the Aladin 2 and is shown in Figure 16.

The proposed aircraft is powered by four Snecma/Rolls-Royce M45H turbofan engines of 7,700 thrust. Cooling of the engine exhaust flow is accomplished in rectangular ejector/silencer units mounted on the lower wing surface behind the engines. The ejectors extend beyond the diameter of the engine nacelles, and a large volume of the ambient airstream is induced to flow through them. Moveable ramps are used at the back of the ejectors to either direct the flow straight back for maximum horizontal thrust or divert a portion of the cooled flow over the flap system during STOL operation. Mixing of the exhaust gases with lower velocity ambient air muffles the nozzle noise of the engines.

The flap system is a double slotted design with Fowler movement. Maximum flap deflection is 70°. In the STOL mode, the flap trailing edge segment is coupled to the ailerons to compensate for engine-out induced rolling moments and lift loss.

Proposed take off procedure calls for initial acceleration with flaps retracted and complete exhaust flow directed aft. As the aircraft approaches take off speed, the flaps are then deployed to 30° or 40° depending on conditions and performance desired. Take off speed is said to be 80 mph and the take-off roll is 450 ft at max take off weight. 940 feet are required to clear a 50 ft obstacle. Maximum range with

90 passengers would be 235 miles with standard reserves. Cruise speed would be 350 mph. In the cruise configuration the M45H engines are said to have a specific fuel consumption of 0.65 lb/lb/hr [8].

Approach speed has been computed at 89 mph with 70° flap deflection. 50% thrust is maintained throughout a typical approach.

Based on production orders for 100 aircraft, Bertin estimates a per unit price of $3.5 million for the Aladin 2.

The externally blown flap concept appears to offer an attractive solution to achieving STOL operation for large transport category aircraft. Engine-out conditions and noise problems should be surmountable with proper design. Cruise speeds, although not in the CTOL jet class, should be quite adequate for the short-stage-length flights involved. Passenger acceptance would undoubtably be much better than for prop driven concepts. At this time no airplane is flying with this concept. One is needed badly for actual flight experience.

Internally Blown Flap

The concept underlying internally blown flaps is the same as for externally blown flaps. Internally blown flaps, however, utilize the addition of internal ducting and nozzles to direct and distribute air over the flaps. While the added components increase the cost of manufacture and maintenance, more quiet operation and stability under engine-out conditions are achieved. The latter is accomplished by cross ducting of engine air so that a substantial unbalance of air flow is not possible.

Extensive analytical and experimental work has been done on internally blow flaps. Figure 27 shows the progress that has been made in this field as well as the increase in suction lift coefficient due to various amount of flap blowing coefficient. (C_μ in the figure is a thrust coefficient). Analyzing the work done, it appears that the most efficient way of improving the lift is by blowing at leading as well as trailing edge; this requires additional study, however. Also, the use of very high blowing coefficients and its impact on ground effect is an area in need of further investigation.

The internally blown flap has been applied by Lockheed to its C-130B turboprop transport. The modified aircraft, designated as BLC-130, utilizes two auxiliary Allison YT-56-A-6 turbine engines to blow high velocity air over flaps, rudder and elevators. Also, a large portion of the lift needed for STOL operation is obtained by deflecting the propeller slipstream. The auxiliary engines have been sized so that one is sufficient to maintain the circulation for STOL operation through all speed ranges. The aircraft performance has been improved to the extent that landing roll is reduced from 1800 feet to 450 feet and the landing speed (at a gross weight of 105,000 lbs) from 105 mph to 70 mph [9].

Another successful application of this concept is PS-1 STOL flying boat of Shin Meiwa Industries Co., Ltd. of Osaka, Japan. Major details of this flying boat is described under the deflected slipstream concept discussion, since 50 percent of the lift during take off is obtained in this manner. Boundary layer control is achieved by blowing air over the upper surface of the flaps, the lower surface of elevators and both sides of the rudder through a rotary jointed duct system as shown in Figure 18. During take off 15% of the lift is achieved in this manner. Also, it has been found that sudden loss of BLC due to engine failure in the STOL configuration does not result in any catastrophic situation [10].

Augmentor-Wing

The augmentor-wing was suggested concurrently by T. Higgens of AVRO Aircraft and J. Bertin, a French scientist. It is actually a form of internally blown flap. The geometry and action of this devise is depicted in Figure 19. High energy air is supplied by a blower situated forward of the flap at the wing trailing edge. The jet issuing from the nozzle is directed in such a manner as to mix with entrained air from the slots provided to obtain an ejector action. This suction action applied to the boundary layer is responsible for increased lift and thrust and is achieved by combining four distinct airflows into a single stream between the two flap surfaces. The individual flow sources are: primary jet flow between flaps, induced flow over the upper surface of the wing, air above the upper flap, and air below the lower flap [11,12].

De Havilland of Canada incorporated this system into the DHC-5 Buffalo, which is a turboprop transport. It's essential features are:

(1) An internal divider running along the length of the circular duct prevents the inflow from two engines mixing so that, in the event of one engine failing, the entire spanwise airflow will be equally affected.

(2) The jet could be directed downward or rearward by incorporating a diverter valve so as to produce vectored thrust.

The Boeing Company is in the process of modifying one of these aircrafts to further increase its STOL performance. Among the modifications planned are the addition of a blowing slot in the vicinity of the leading edge and an auxiliary flap to partially choke the augmentor exit. The latter, known as the "augmentor choke", can serve the following purposes: (1) provides roll control if fitted to the outboard section; (2) serves as a lift dump or thrust reverser immediately after touch down if fitted over the full span; and (3) provides a means for control of the glide path by acting in opposition, thus producing a choking action, if fitted to both upper and lower flap elements. The latter arrangement is preferable to the use of blown ailerons which tend to generate adverse yaw.

The performance of this aircraft is being carefully studied in wind tunnel tests. The two methods of flight path control -- the use of throttle modulation and the modulation of the Pegasus vectored thrust nozzles -- are among the high priority objectives for investigation. The former method, adopted in all CTOL operations, is found to exhibit loss in stall at high decent ratio and poor response characteristics. The latter method, especially incorporated in this vehicle, proved to exhibit quick glide path recovery. It has also been found that strong suction pressure produced at the flap intake provides powerful mid-chord separation control, which results in gentle stalling characteristics.

Landing approaches under severe weather conditions were also studied through wind tunnel simulation. They were conducted under a gust condition of 35 ft/sec, while simulating an approach of 60 knots. Tests of the model subjected to 30 knots of cross wind have also been performed; they showed that very little bank was required to produce side-slip. In a ground effect test, it was observed that the augmentor jet deflected downward, the flow pattern was distorted, resulting in a loss of lift.

Boeing is also conducting wind tunnel tests on swept wing model of the Buffalo at the NASA Ames 40' to 80' Wind Tunnel. Limited tests conducted have shown a reduction in flow disturbance at the wing root junction and that a nose down pitch observed between $\alpha = 20^\circ$ to 30° will offset the pitch up tendency usually observed in swept wings. Adequate separation control at the leading edge can be achieved by a mechanical slat thus eliminating the cost of leading edge blowing.

The research work conducted in the past five years in the augmentor wing field suggests that this concept is going to be one of the most successful STOL approaches of the future. Still, there is lack of analytical data. Also, further tests that are scheduled to be conducted at NASA Ames on swept wings will provide information essential to future development [13].

Direct Boundary Layer Control

The terminology "direct boundary layer control" will be applied to those concepts and methods of controlling boundary layer separation by any means that is not exclusively associated with the propeller slipstream and flow over control surfaces. Generally it can be thought of as a broader category of separation control which usually involves energizing the flow over entire lifting surfaces.

The usual approach employs blowing at the leading edge and sucking the boundary layer through slots on the upper surface of the wing. The slots are essentially uniformly distributed over the entire wing so that uniform suction is obtained. This approach has been pioneered at Mississippi State University; a complete airplane has been designed and built by the MSU team for STOL research. Designated the XV-11A, the craft is a two place, high tapered wing, fixed gear, pusher propeller vehicle constructed entirely of glass fiber-reinforced polyester plastic materials. A shrouded pusher propeller is mounted on the aft fuselage and is powered by a GE T-63-A5A(FE) gas turbine (Figure 20). The boundary layer control (BLC) system blower and ducting is housed in the fuselage. A camber changing mechanism bends the upper skins of the wing which varies the camber to obtain a deflection of 0 - 30° in order to vary the lift coefficient. The upper surface of the wing is drilled with many small holes to provide distributed suction [14].

The BLC system consists of a centrifugal blower and appropriate ducting. Ducts connect the blower to wing roots and exhaust outlets located on the side of the fuselage. The interior of the wing acts as a plenum for the suction system and is under a pressure of 15" of water below ambient pressure. Flight instrumentation was supplied by USAA Laboratories and Mississippi State University.

The aircraft's approach and cruise trim speeds are 70 to 120 knots respectively. Tests were conducted with the BLC system operating as well as with the blower disconnected and with the suction holes sealed as well as open. Flight performance and longitudinal static stability data were obtained for a take off weight of 2,690 pounds. (There is no wind tunnel data for this aircraft). The maximum speed reached was 159 knots in level flight and there was no warning when the aircraft entered stall. Aircraft pitch up at 80 knots and climb out at 90 knots with zero wing camber gives satisfactory take off performance with a ground roll of 2,000 feet and a climb rate of 100 fpm. Reverse propeller thrust is used to improve the rate of sink.

A number of problems associated with this aircraft, such as extremely high noise levels, poor radio communication due to static charge built up on the plastic structure and large longitudinal control forces, have hindered the progress of this research. However, it has been observed that failure of the BLC system does not present any hazard and a shrouded propeller provides increased low speed thrust.

Another flight test program conducted by the MSU researchers utilized a L-19 airplane modified for STOL operation (Figure 21). The modification consisted of (1) alteration of the size and shape of the vertical fin and rudder for directional control at low forward velocity, (2) addition of end plates to elevators for improved effectiveness (3) addition of end plates to both ends of the leading edge flaps to reduce induced drag due to spanwise load fluctuation, (4) addition of trailing edge suction ports, and (5) modification of the wing leading edge geometry to suppress local separation. With these changes the following improvements were observed:

(1) Reduction in take off distance to clear 50' obstacle by 38 percent. A total of 420' with ground roll of 220' was required to clear 50' obstacle (Figure 22).

(2) Landing distance was reduced through 210' to 580'.

(3) Lift coefficient was improved from 2.86 to 5.74 with 20° flaps and aircraft airspeed of 30 mph, Figure 23, and

(4) Considerable reduction in power required to fly at low speeds by using flaps.

The resulting boundary layer profiles are shown on Figures 24, 25, and 26. The sudden loss in energy of the boundary layer at the 50 percent chord position with full flaps can be seen from the increase in loss of momentum thickness shown in Figure 27. δ^* and θ are boundary layer displacement thickness and momentum thickness and $H = \delta^*/\theta$.

Since the available information on direct BLC is limited it is difficult to project the future of this approach. Clearly slots and ports in the wing will interfere with the stress distribution in the structure, for example, the modified L-19 tests are encouraging, however, and additional analytical and experimental research may lead to concept refinements [15].

Rotating Cylinder Flap

The rotating cylinder concept involves energizing of the boundary layer by a suitably placed rotating cylinder projecting into the airflow over the wing upper surface, Figure 28. If the tangential velocity at the upper surface of the cylinder is sufficiently higher than that of the airflow, a momentum interchange occurs mechanically between the cylinder and the boundary layer. In this way, the airflow may be induced to follow the contour of a highly deflected flap without separation.

This concept has been utilized by North American Rockwell Corporation on their OV-10 NASA STOL prototype shown in Figures 29 and 30. The basic OV-10A airplane is in service with the Air Force, Navy, and Marines fulfilling such mission roles as close support and armed reconnaissance. Aircraft empty weight is approximately 6,890 pounds; maximum take off weight is about 14,400 pounds. Stall speed of the basic OV-10A is approximately 125 knots at 8,000 pounds.

The modified prototype is equipped with T53 turboshaft engines replacing theT76 engines in the service model. It employs cross shafting between the propellers to provide engine-out control in the STOL mode. Also, larger propellers are installed.

The rotating cylinders are machined aluminum. Wall thickness is 1/4 inch; diameter is 12 inches. They are driven by hydraulic motors which in turn are driven by pumps mounted on the engines. The cylinders are designed to rotate at 9,700 RPM at 50 knots: this provides a U/V ratio of 6.0, where U is the tangential velocity of the cylinder surface and V is the free stream velocity. Maximum flap deflection angle is 90°.

The project goal was to provide a stall speed of 40 knots and a take off roll of 505 feet. Planned approach speed is 50 knots at a -8° approach path angle.

This airplane is currently undergoing flight testing at NASA Ames Flight Research Center. Information available to date indicates it is fulfilling design expectations.

Lateral (Spanwise) Blowing

The concept of lateral blowing has been discovered within the last several years by the Aerospace Sciences Research Laboratory of the Lockheed-Georgia Company. The concept consists of blowing a jet of high-momentum air from the side of a fuselage over the low pressure side of a lifting surface. Combination of this jet of air with the vortex formed by leading edge separation at high angles of attack causes free stream air to be entrained into the jet, which prevents the vortex from shedding.

Figure 31 shows the relative efficiency of the spanwise blowing concept to that obtained from the pure jet-flap concept. It shows that for C_u of 0.35 and above the lifting efficiency of spanwise blowing is of the same order of magnitude as the pure jet flap [16].

Figure 32 shows how the jet controls separation experienced on a jet-flap equipped wing at a 20° angle of attack in the smoke tunnel.

In addition to blowing over a basic wing to provide lift augmentation, tests have been conducted in blowing over a trailing edge flap. They have shown that flow separation from trailing edge flaps may also be controlled by this concept. This raises the possibility of blowing over flaps as a modification to existing aircraft to increase attainable C_L values.

In addition to use of a basic high-lift system by blowing over the wing and/or flaps, the concept has the following potential applications [6]:

(1) Increase control effectiveness by blowing over tail surfaces during V/STOL operation.

(2) Increase aileron effectiveness. This could aid engine-out control in the STOL mode.

(3) Control of leading edge separation caused by high-lift flap systems.

Only very basic research has been done on this concept. Further research is contemplated to determine lift, drag, and pitching moment data as well as the effects of nozzle shape, size, and inclination, and leading edge geometry.

CHAPTER III

TURBINE ENGINE VECTORED THRUST CONCEPTS

Lift-Cruise

General

Lift/Cruise terminology as used herein is that V/STOL configuration where the powerplant serves a dual purpose, namely, the production of thrust for cruise and the production of thrust for vertical lift.

The aircraft which at present epitomizes the lift/cruise concept is the single engine Hawker-Siddeley Harrier (Figure 33). The Harrier holds the distinction of being the world's first V/STOL operational fighter aircraft. This historic first occurred in the summer of 1969 with the activation of the Royal Air Forces initial squadron of V/STOL aircraft.

Interest in this aircraft is in no way limited to the RAF as evidenced by the U. S. Marine Corps receiving funding of 60 Harriers. The first eight of the 60 funded are now being flown regularly at the Marine Air Station in Beauford, South Carolina.

Historical Development

One of the earliest experimental aircraft of note in this category was the X-14 developed by Bell Aircraft Corporation under a USAF contract granted in 1955. The aircraft was powered by two Armstrong Siddeley ASV 8 Viper turbojets, each producing 1,750 pounds of thrust. A system of cascade directors (Figure 34) in the jet pipe allowed the thrust to be vectored between the vertical and horizontal.

The X-14 completed its first hovering flight in February 1957. Complete transition from vertical to horizontal flight was accomplished in May, 1958.

In 1959 the X-14 was delivered to NASA Ames Research Center. The Viper engines were replaced by two General Electric J85-GE-5 turbojets and an Ames designed variable stability and control system was fitted into the aircraft. With these modifications it became known as the X-14A, shown in Figure 34.

The X-14A enabled NASA to determine a range of control power and damping boundaries for a hovering VTOL aircraft [17].

In 1957 Hawker Aircraft Ltd. began studies for the purpose of developing a light weight V/STOL strike reconnaissance aircraft. At this time the evolution of the Harrier aircraft as we know it today began. This evolution was in no way through an ordered development as at one time or another the Harrier and its predecessors, the P1127 and Kestrel all had precarious existences often close to cancellation. "At various times they were saved by Hawker Siddeley, the RAF, and several sources in the U. S. Department of Defense." [18]

> "The basic Harrier design grew out of an idea by the French engineer, Michel Wibault, who suggested the use of four nozzles for vertical lift, each fed by a centrifugel blower, with all the blowers driven by a turboprop engine. USAF officers working in Paris for the Mutual Weapons Development Program during the mid-1950's were instrumental in persuading Bristol Engines in Great Britain to reduce the weight of the powerplant by attaching the four nozzles to a large turbofan." [18]
>
> "The USAF also played an important role in persuading Hawker to design an airframe around Bristol's Pegasus engine on which serious design work had started in 1956. Design of the P1127 airframe was well under way by 1958 and manufacture started in 1959. First hover trials took place in 1960, transition was achieved in mid 1961 and supersonic speeds were recorded later that year." [18]

Figure 35 shows a Pegasus engine.

Of particular note is that early in the development of the BE53 Pegasus engine the fan and high pressure compressor were bladed so as to contra-rotate in order to minimize gyro cross-coupling in V/STOL flight.

Early experience in flight with the P1127s revealed a necessity to improve the wing design and the horizontal tail. The resulting design was the classic sweptback wing planform and the anhedral tailplane which are both features of the Harrier today.

It was the above mentioned modifications that gave birth to the Kestrel whose first flight was in February, 1964. The Kestrel was powered by a Pegasus 5 engine rated at 15,200 pounds static thrust. This was the first jet V/STOL aircraft to be granted a Service Release, including night flying. "Owing to the economics of the three nation program (U.K. U.S.A., Federal German Republic) the Kestrel's ability to carry and deliver armament was never fully proven and developed." [19]

Following the first hovers of the P1127 prototype the Hawker design team began working on a second generation type aircraft. This aircraft was to be designated the P1150 with a configuration capable of supersonic flight. The powerplant was to employ Plenum Chamber Burning (PCB) for the purpose of burning fuel in the exhausted fan air from the two forward nozzles. PCB was always to be used for V/STOL flight as without it the thrust center would have had an unacceptable movement relative to the aircraft center of gravity [19,20]. This particular aircraft was never funded due to the fact that it was too small to meet the final design specifications.

Following this the P1154 supersonic design was conceived around the Bristol 100 vectored thrust engine with PCB. This design attempt also ended in cancellation as with its predecessor the P1150. However with the cancellation of the P1154 a simultaneous announcement was made that the RAF could begin work on the development of an advanced version of the Kestrel for a potential use as a close-air-support V/STOL fighter. It was this decision that led to the P1127 (RAF) which became known as the Harrier in 1967 [19].

It is the intent now to take a close look at the Harrier with respect to its technological and performance aspects.

Harrier Technology

Powerplant. The Pegasus type engine which presently powers the RAF Harrier is the MK 101 (Figure 35). This engine is a straight flow, twin spool, turbofan jet propulsion engine with a bypass ratio of 1.44 to 1 at V/STOL rating. Its design serves a threefold purpose in that the total thrust can be rotated so as to meet the requirements for V/STOL, conventional flight, and also reverse thrust for braking.

Thrust vectoring as mentioned above is achieved by rotating the four Pegasus jet nozzles through angles from 0° to 98.5° (Figure 36), where zero degrees would be the conventional flight position.

The two front nozzles are termed (cold) as they receive air only from the low pressure compressor (Figure 37), whereas the two rear nozzles receive the hot discharged gases that have been expanded across the high pressure and low pressure turbines.

Of extreme importance for V/STOL flight is that the total thrust vector must pass as close as possible to the center of gravity irregardless of nozzle positioning. This condition is satisfied in the Harrier aircraft [21].

The Rolls Royce Bristol MK 101 engine develops 19,000 lbs of static thrust. As previously mentioned it is this engine that the RAF has in its aircraft. The Pegasus engine that is presently in the exported U. S. Marine version is the MK 102 which develops 20,500 lbs of static thrust and has a T/W ratio of 5.57. Plans are to retrofit the RAF with the Pegasus 11 (21,500 lb. s.t., T/W of 7.67). Consideration is also being given to the possible use of the Pegasus 15 with Plenum Chamber Burning (24,500 lb s.t.).

Stability and Control. For the V/STOL mode of operation a means of control other than those which react to aerodynamic pressures must be employed. The Harrier uses a jet reaction control system (Figure 38). Control is achieved by the positioning of control valves at the extremeties of the aircraft. The gases used are routed from the 8th stage of the compressor. Air to the jet reaction system is automatically turned on when the engine nozzles are rotated beyond the 20° position. The reaction controls are linked to the stick and rudder pedals so as to produce aircraft response to control inputs in the normal sense.

Initially the P1127 aircraft in unautostablished hover experienced divergent lateral oscillation due to control sensitivity. Even though the aerodynamic damping effects are small, it was determined that considerable benefit could be derived from the forces present if control sensitivity was properly chosen. Improvements in this area led to unautostabilized flight with no significant problems experienced.

In the lateral-directional mode as speed is reduced the directional stability decreases. This was found to be largely due to the air intake flow as some 400 lb/sec of air are brought to rest in the air intake at high power settings. In forward flight this produces a drag force that tends to turn the aircraft out of the wind since the air intake is ahead of the center of the gravity [19]. The effect is a directional instability below 50 knots at which time the rudder becomes effective. This instability is controllable due to the inertial forces provided by the fuselage coupled with the yaw reaction control jets and rudder.

In the early testing of the P1127 it was found that the undercarriage was responsible for a significant control problem in bank and yaw. During take off it was found that the main undercarriage leg extended more than the outriggers. As a result the aircraft banked uncontrollably and the ensuing horizontal component of lift force moved the aircraft sideways in a skid on the main wheels. Control could have been accomplished but at the expense of a considerable amount of bleed air with the associated reduction in engine performance.

The fix here was to design the main gear with a two stage oleo. On touchdown the strut shortens but allows no rebound for the first 7 inches of travel. Because of this the aircraft rests firmly on its outriggers and does not rise until lift exceeds weight [22].

Air Intakes. This aspect is very important to V/STOL flight as the intake must be sufficiently large to provide the mass flow required for VTOL flight where the engine must operate a practically full throttle.

The large intake unless extremely well designed will most certainly produce large drag counts in the conventional flight regime. Thus in designing a V/STOL fighter the air intake for high efficiency in the V/STOL mode cannot be allowed to compromise performance in the high speed arena.

In conventional flight the airflow required by the engine is relatively modest as compared to that needed during VTOL. The result is a large amount of air spillage. This spillage (airflow diverted outward past the lip of the air intake) indirectly increases the aircraft drag. At high subsonic speeds the local airflow outside the intake lip goes supersonic. Sufficient spillage into the supersonic region will tend to strengthen the shock wave with a resulting separation in the boundary and then the inevitable drag increase. Harrier engineers used a concept shown by Mr. H. H. Pearcey of the National Physical Laboratory. This concept deals with the shaping of rounded nose airfoils and states. "It is possible to shape rounded nose airfoils in such a way that supersonic flow develops in a limited region and slows down again with only a very weak shockwave at the downstream boundary, and thus a drag little more than expected for a completely subsonic flow."[19] The resulting work led to a spillage drag of modest proportion in all cruising conditions.

Harrier Performance

The discussion following will be indicative of the present RAF Harrier with the MK 101 engine unless stated otherwise.

Basically the Harrier has a capacity payload of 13,000 pounds which would consist of 5,000 pounds of fuel plus 8,000 pounds of ordinance. This gives a take-off gross weight (TOGW) at 24,700 pounds. Should a vertical take-off be desired then obviously the TOGW will be decreased. The maximum TOGW for a VTO is 15,450 pounds. Adding and subtracting several numbers gives a capacity disposable load of 3,750 pounds for VTOL. Obviously should a VTOL be required the mission will most assuredly dictate the breakdown of the 3,750 pounds between fuel and ordnance. A realistic analysis would be to consider that the terrain would allow some form of short take-off. The disposable load will increase approximately 6 pounds for every foot of forward roll added to the take-off [23].

The rolling VTO and STO are advantageous not only with respect to disposable load but also in preventing debris and hot gas reinjection. Should the VTO or near VTO be required a large matting would be required to prevent reinjection. The matting presently being used is made out of aluminum, usually in the sizes 50' x 50' or 100' x 100'.

With the introduction of the Pegasus 11 and possibly the Pegasus 15 engines the VTO performance will most certainly be improved.

Based on conversations with test pilots and articles presently available in the literature it appears that pilotage in hover and transition present no major problems to the average fighter pilot. In the Harrier the pilot has one extra handle on the throttle quadrant to be concerned with. This is the nozzle lever which controls the position of the four nozzles: "Full forward for horizontal flight, full back (about 98°) for reverse thrust, 80° for vertical flight, and anything less for STOL," [23]

In conventional flight there is an excess amount of thrust available due to the high thrust to weight ratio of the engine and relatively light aircraft structure. Also in this flight regime the pilot has thrust vectoring available which needless to say amounts to an extremely effective speed brake. Thrust vectoring is now being investigated by the users of the Harrier with respect to air combat maneuvering and weapons delivery.

Conclusions

The Lift/Cruise configuration enjoys a simplicity of design with a by-product of easier logistical support than some of the more complicated V/STOL design. For a V/STOL fighter to achieve its operational goals ease of maintenance and means of minimizing sophisticated support requirements must be considered from the outset. This configuration is very adaptable to technological improvements as evidenced by being able to retrofit existing aircraft with improved engines. In addition the Lift/Cruise engine has considerable excess thrust available that can be used to advantage in a combat environment.

As to the disadvantages, one is that the engine is grossly oversized for an efficient cruise operation. Another that stands out is the thrust reduction due to the use of compressor bleed air for the reaction controls. Problems also arise due to the negative ground effect and hot gas recirculation caused by the hot, high velocity exhaust gases impinging on the ground in close proximity to the vehicle [24]. The noise levels associated with the lift cruise engine can be accepted by the military but until there are some significent technological breakthroughs in noise abatement the Lift/Cruise configuration has little chance of any real commercial acceptance.

Integrated Propulsion/Air Frame

General

This particular fan concept is best illustrated by the Ling-Temco-Vought propulsive wing shown in Figure 39. The beginning of the propulsive wing concept dates back to 1958 when LTV began studies on integration of the structural, aerodynamics, and propulsive systems into a vectored thrust vehicle which would have hovering and high speed capabilities [25].

The following discussion will be concerned with the LTV ADAM IV aircraft concept (Air Deflection and Modulation), shown in Figure 40,[26],

Current Technology

Propulsion System. The propulsive system shown in Figure 41 consists of two gas generators which supply hot products of combustion to the four turbines located directly behind the vertically mounted wing fan assemblies. As can be seen the gases from one generator are routed to the turbines of the inboard fans whereas the gases from the other generator are routed to the outboard fans. This system provides symmetric control in the event of engine failure.

With respect to the ADAM system the augmentation ratio is defined as, "The thrust exerted by the turbofans to the thrust that would be exerted by the gas generators used as turbojets," [26] High bypass ratios are necessary to provide sufficient net thrust for the V/STOL flight mode. Figure 42 indicates that design point bypass ratio has only a small effect on net thrust in the upper subsonic speed regime. This indicates that the gas generator could be sized for cruise and then implemented with a sufficient fan size for the required static thrust. The problem with this reasoning is that there is no real control of aircraft size. The present technique is to use larger gas generators and smaller fans to provide the required static thrust. The penalty paid in doing this is a degradation in Specific Fuel Consumption (SFC) during the cruise mode of flight since the large gas generators will be operated at reduced power settings. The advantage of this approach is that a smaller aircraft can be designed with a decrease in empty weight [26].

The propulsive wing thickness is determined by the fan size and allowances for structure over and under the fan. A typical thickness chord ratio would equal 0.25. For drag divergence calculations a lower t/c can be used due to the fact that much of the flow passes through the wing rather than around it. This leads to the concept of an equivalent thickness ratio obtained by removing the thickness in the undisturbed flow of the stream tube passing through the wing [26]. A collapsed wing profile is shown in Figure 43.

Thrust Vectoring. Thrust for hover, transition, and cruise is obtained by vectoring the fan efflux and turbine exhaust as shown in Figure 44. The turbine exhaust is vectored over the trailing edge flap by the Coanda effect.

Lateral control in hover is possible through differential thrust obtained by supplying one turbine with more hot gas than another.

Longitudinal control is obtained by diverting a small portion of the flow of each wing fan into ducts leading to vertical nozzles at the front and rear ends of the airplane [26].

Control in yaw is obtained by differential deflection of the vectoring systems on either side of the aircraft through an angle of $\pm 10^{\circ}$ from the vertical.

The following discussion is included to present a concept that combines the propulsive wing and jet flap ideas.

Propulsive Wing/Jet Flap. This concept involves the mixing of the fan and exhaust gases and then exiting them through slots that extend the trailing edges of the wing. In cruise flight the entire jet exhaust would exit from the trailing edges. It is in the V/STOL mode where this concept comes into its own. Figure 45 shows two opposing nozzles that are fed by the mixed fan and exhaust gases. The forward nozzle (1) is the same exit that would be used during cruise flight whereas nozzle number (2) would only be in operation during V/STOL flight. With both nozzles open there would be two high speed flows rushing towards each other along the entire trailing edge. Due to the Coanda Nozzle effect these flows would begin turning immediately after exit nozzle 1 and 2. The desired effect here is a large thrust augmentation. From available information 47% augmentation has been achieved. Figure 46 shows a Coanda Nozzle Test with nozzles 1 and 2 from the previous schematic penciled in. This figure shows the air entrainment by the mixing of water with the jet gases. It can be seen that the flow is turning the 90 degree corner exceptionally well.

Problems with this type augmentation tend to develop as the exit velocities from nozzles 1 and 2 increase. This is caused by an inability to turn the corner immediately after nozzle exit. The associated problem is a loss in mass flow out of the Coanda Nozzle.

Conclusion

The basic advantage of the propulsive wing is that it enables an efficient integration of three generally separate disciplines: structures, aerodynamics, and propulsion. In so doing an overall reduction in aircraft weight along with improved wing aerodynamics has been achieved.

As to the disadvantages problems do arise in wing analysis which cannot be related to conventional wings. Another problem is that of hot gas ducting. In an attempt to push turbine inlet temperatures even higher, the point where a break through is needed is material technology for hot gas ducting is rapidly being approached.

Jet-Lift

General

Jet-lift V/STOL aircraft are defined as those using pure turbojet or integral drive turbo fans for direct lift. Remote driven fans will be discussed in a later section. Several types of airplanes have been built or conceived with the use of lift-jets to augment cruise engines to obtain a VTOL capability. The discussion of this topic will be in two parts, the lift engine and aircraft examples deploying a composite propulsion system.

Lift Engine

The lift engine approach is the use of lift engines, either turbojet or turbofan, to produce all or part of the vertical lift capability. Considerable research is in progress at the present time to develop this system. This system uses lift engines whose high velocity exhaust is directed downward during vertical take-off and landing. Once the aircraft has progressed through the transition phase and has obtained wing-borne speed, these engines will be shut down during cruise.

Development. First generation lift jet engines ran as early as 1955 at a thrust/weight ratio of 8.7. Second generation engines were improved to a thrust/weight ratio of 16/1. Now under development are the third generation engines with approximately 20/1 [27]. Various figures are quoted as to the thrust/weight ratios but it was found that there is no set standard for rating jet engines. Today we are operating at turbine inlet temperatures ($T4$) of 1800°F. By 1985, engines should be operating in the range of 2800°F to 3700°F and at a thrust/weight ratio of about 24/1. Also during this period overall pressure ratios of 22 and 40 for turbojet and turbofan engines respectively can be expected. Added advantages of small volume and short length have been emphasized as a result of many aircraft project studies and it is expected that future liftsets will offer a significant advance in these respects also.

Requirements. Lift jets must be very powerful, yet small in size, light in weight and less costly than cruise jet engines. Since they are used only during the vertical and transition phases of flight, run time is approximately 10 minutes per aircraft flight. The lift jets run only at low aircraft flight speeds (usually less than 200 knots) and rarely above 10,000 feet altitude. These flight conditions ease the control system problem and reduce the range of temperatures and pressures to a point below which the cruise engine must work. "Thus lightweight constructions are possible and - perhaps most important - high strength, low weight and low cost plastics can be introduced. Modern glass-reinforced plastics, when scientifically used in the RB 162, are as strong as steel yet lighter than aluminum." [27] Another very important requirement of the lift-jet is its ability to change its amount of thrust very quickly. Response time today is about 1/4 sec for turbojet and 1/2 sec for turbofan engines. Lift engines should also be equipped with vectoring devices to supplement flight controls at low speeds.

Characteristics.

> "Lift jets are often controlled as a group by a single throttle lever in the pilot's cockpit, just as the cylinders of a piston engine work together. They are fed with air through a common intake and are often fitted into a single lift jet bay. Special considerations have to be taken into account if the simplicity of a light weight, compact, basic engine is not to be lost once a group of engines are fitted together into an aircraft.
>
> The main items the lift jets require for their normal operation include; the intake, which turns the air on to the engine compression front face, the puff pipes which connect each engine to a common puff-pipe system which in turn feeds the aircraft puff-pipe nozzles, and the intake and exhaust doors which close off the lift bay during cruise flight to reduce aircraft drag." [20]

Lift jets should be capable of operating under air intake conditions which are very much more severe than those normally experienced by the cruise engines. Since they are mounted vertically and must run during forward flight, there is considerable cross-flow across the intake face and, with the short intake usually demanded in a lift-jet installation, a correspondingly high distortion at the compressor inlet.

Perhaps one of the most interesting features of modern lift jets is the successful development and use of composite materials for a major part of the engine.

> "The material used for the cold part of the engine is glass fiber in an epoxy resin matrix. The manufacturing process has been developed so that by pressure moulding, components can be moulded with sufficient accuracy such that subsequent machining is unnecessary. The main advantages are; high strength, low weight (specific gravity similar to magnesium), low cost when produced in quantity and high internal damping characteristics." [27]

Lift jet engines are normally designed for simplicity, and ease of maintenance. The absence of engine accessories, normally fitted to the cruise engine, simplifies the task of engine , simplifies the task of engine inspection and permits rapid daily and periodic inspections. The lift-jet engine is not a short life engine, being designed for a minimum of approximately 6,000 cycles.

Also a basic design critıon is to provide an engine with an installed life between overhauls and reliability comparable to that of the main cruise engines [27]. Noise is the greatest specific problem associated with the lift-jet engines. Noise levels for the turbojet are very high and unless attenuating systems such as slit nozzles are used to reduce the noise, this one disadvantage will be predominant. Noise levels for the lift fan engine are moderate and future developments such as the General Electric quiet engine program should improve noise abaitment to an acceptable level.

Aircraft Deploying a Composite Propulsion System

A composite propulsion system is one that in order to obtain vertical flight, cruise engines must be augmented by direct lift engines. There are basically 3 types of split propulsion systems; cruise plus direct lift; deflected lift/cruise plus direct lift; and vectorial lift/cruise plus direct lift.

Early developments in the use of lift jets only, was done in 1952 with a test vehicle called the "Flying Bedstead."

> "It was designed to use two Rolls-Royce Nene jet engines placed back to back with their exhaust pipes meeting at the center of the machine. Here the exhaust pipes bent downwards to provide vertical lift. The 'Flying Bedstead" proved conclusively that a vehicle could be sustained in flight supported only by the thrust of powerful jet engines and, even more important, that practical means could be devised to control it." [20]

Cruise Plus Direct Lift. The cruise plus direct lift system uses lift engines only for the vertical portion of flight. The cruise engine only supplies thrust for wing borne flight. Both lift and cruise engines are used in the transition phase.

After investigating the "Flying Bedstead", without aerodynamic surfaces, the Short S.C. 1 research aircraft was then built. It was powered with four lifting turbo-jets (RB 108) located centrally in its delta wing planform and an additional turbo-jet solely for propulsion. This test vehicle was capable of taking off and landing vertically and used to investigate the problem of transition from vertical to horizontal flight.

The converted Mirage/Balzac experimental VTOL aircraft by Dassault in France was a logical step following the Short S.C. 1 (Figure 47). It has 8 - RB 108 lift jets and one Orpheus cruise engine installed in a Mach 2 capability air frame configuration of smaller frontal area than the S.C. 1. Its prime role is as a test vehicle for the inflight testing of the composite power plant system, investigation of the aircraft's stability at low speed and in hover, and evaluation of slow flight characteristics.

The VJ 101 C is a completely new application of the lift jets as shown in Figure 48.

> "Two engines are in the forward section of the fuselage and operate in the normal manner as lift jets. Four are installed in two swivelling wing tip pods which rotate into the vertical position for VTOL. Special variable intakes were developed successfully to give satisfactory engine functioning during aircraft transition. The VJ 101 C also uses direct modulation of engine thrust for aircraft roll and pitch control, and modulation or pod tilt for yaw."[28]

This is thought to be the first time this method has been used as a flying control. The classification of the VJ 101 C should actually be classified as a tilt lift/cruise plus direct lift system.

The Flagon "B" is another interesting VTOL aircraft that would be an example of the cruise plus direct lift system (Figure 49).

<u>Deflected Lift/Cruise Plus Direct Lift</u>. As shown in Figure 50, deflected thrust from the cruise engine is used in addition to the lift engines for vertical flight. Several research aircraft worthy of mention with the type of propulsion system are:

XV-4B(Figure 51)

NASA Research Vehicle (Figure 52)

VJ 101B

VJ 101D

NATO Fighter

The XV-4B, built by Lockheed-Georgia is a typical example of this type system and will be discussed in detail.

"The XV-4B is a six engine jet lift plus lift-cruise VTOL airplane. Four YJ85-19 lift engines are mounted vertically in separate compartments in the center fuselage and two YJ85-19 lift-cruise engines are mounted horizontally in nacelles adjacent to the fuselage. Diverter valves are provided on the two lift-cruise engines for diversion of cruise thrust to the lift mode. Six swiveling, fixed area exhaust nozzles are provided for vectoring of lift thrust. The exhaust for cruise propulsion is via fixed area jet nozzles. Reaction controls utilizing compressor bleed air are incorporated for aircraft stability requirements on all three axes and operate in conjunction with the conventional aerodynamic controls.

A ducting system directs compressor bleed air from each engine to dual visor type control valves at the wing tips and at the fore and aft extremities of the fuselage. These valves, which provide aircraft reaction thrust on a demand basis, are linked mechanically to conventional aileron, elevator and rudder surfaces.

Limited directional control of the vertical thrust vector is provided by a system of swiveling convergent nozzles on the lift tailpipes which are hydraulically powered and mechanically interconnected. These nozzles exhaust through a pair of hydraulically powered exit doors which can be closed in the conventional flight mode when the four vertical engines are shutdown and the two horizontal engines are exhausting aft.

Pilot controls in the side-by-side cockpit are quite conventional with the additional controls peculiar to V/STOL flight. These include throttles for the lift-cruise engine, combined collective throttles with individual trimmers for the four lift engines, a mode select switch which controls the exhaust doors and the control systems gains, a control switch for lift-cruise engine diverter valves, and a swivel nozzle position trimmer switch." [29]

The internal design is centered around the engine arrangement, with the cruise engines installed in such a position as to permit the thrust to be diverted to the lift mode through the center-of-gravity and the four lift engines grouped closely around these lift nozzles as physically possible to minimize adverse moments about the center-of-gravity with the thrust vector changes or engine failure.

All six engines supply bleed air to the reaction control nozzles when the airplane is in the VTOL flight mode and engine RPM exceeds 80%. The 80% minimum bleed limitation protects the engines from being overbled, since the reaction control system requires bleed on demand from flight control system inputs, and the only valves controlling the flow during bleed operations are the reaction control valves. (Figure 53). Each valve has dual visors, so that in the event of a failure of one visor, such as in a jammed open (or closed) case, the other visor will function to provide partial control response. The roll valves thrust downward on one wing tip and upward on the other on a given command, producing a true couple on the airplane, while the pitch and yaw valves produce a force and moment. A common manifolding of the bleed air imposed a prime reliability requirement on the bleed ducting system, because a major failure in the duct system would most likely result in loss of the aircraft.

All six lift tailpipes in the XV-4B were equipped with vectorable nozzles, with the system designed to provide a vector capability of $\pm 10^{\circ}$ about the normal position [29].

> "The design requirements for lift engine inlets in V/STOL aircraft are severe. This severity evolves because the lift engine must be installed with minimum weight, volume, and frontal area; because engine airflow must be decelerated from flight speed to a considerably lower inlet velocity and turned approximately 90°; because engine airflow must enter with minimized pressure loss and pressure distortion; and because an inlet system of simplicity and reliability must be provided to operate over a wide range of relative freestream velocities and engine power levels.
>
> A number of experimental research programs have been conducted related to the design of multiple lift engines in a pod. Studies included tests of inlet configurations involving retractable scoop-type inlet closure doors; individual doors for each inlet; large doors for two or more inlets; and a simple retractable cascade mounted ahead of the front inlet and single auxiliary lips for the remaining inlets in a multiple unit pod. The test results for all scoop-type inlet configurations indicated that pressure-operated louvers would be required in the door or that the door position would be varied as a function of free-stream velocity to improve the inlet pressure

recovery at low flight speeds and high engine powers.

The program discussed here was concerned with the development of lift engine inlets for the XV-4B aircraft which would provide satisfactory inlet performance for all modes of VTOL flight. The use of ram air for in-flight engine starting was not a requirement since turbine impingement started using lift-cruise engine compressor bleed air was to be incorporated; however, favorable windmill characteristics were desirable to minimize bleed air requirements. The inlet configurations tested in this program were designed to be independent of inlet closure door considerations and were developed on the premise that a fixed-geometry inlet would satisfy the XV-4B requirements." [29]

"Twenty-three flights were completed with the XV-4B, exploring conventional flight phases and the high-speed end of VTOL transition flight. Numerous in-flight engine starts were made, and flights were made in this configuration at lift engine powers up to approximately 90%. Diversion of the lift-cruise engines to the lift mode had been accomplished on one flight, which included operation down to approximately 90 KIAS. No undesirable aircraft transients were associated with diversion of the lift-cruise engines. Pilot Techniques for decelerating the aircraft were being explored, and during these explorations the only noteworthy problem appeared. While decelerating the airplane with all four lift engines running above the 8-% minimum bleed power setting, an intermittent tail-buffet condition was observed at speeds between 125 and 140 KIAS. In the limited exloration of this phenomenon that was made prior to loss of the aircraft, the onset of the buffet condition seemed to be related to vector nozzle position, but this was not fully explored. In any case, the magnitude and frequency of the buffeting was not such as to cause any particular concern other than searching for an understanding of the reasons for the occurrence of the condition. No other significant in-flight problems were observed."[29]

Vectored Lift/Cruise Plus Direct Lift. A typical example of the vectored lift/cruise plus direct lift composite propulsion system is shown in Figure 54. The US/FR6 strike fighter (Figure 55) uses thrust vectored from the two main cruise engines plus swing-out lift engines to obtain vertical flight.

One of the latest V/STOL prototypes is the VFW-Fokker VAK-191B tactical reconnaissance fighter (Figure 56). It was first shown at the VFW GmbH Factory at Bremen in April 1970. It has two Rolls-Royce/MAN RB. 162-81 lift jets and a single RB. 193-12 for forward propulsion and will be used as a systems tested for the British-German-Italian multi-role combat aircraft (MRCA). "Rolf Riccius of VFW said the VAK-191B will be used to test the MRCA fly-by-wire system as well as the APU, hydraulic and pneumatic systems and wheel and parachute braking."[30]

The most advanced V/STOL aircraft tested by NASA, is the Dornier DO-31 which was built under contract from the West German Defense Ministry (Figure 57). Basic power is provided by two B.S. Pegagus 5 vectored thrust engines with three R.R. RB-162 vertical lift engines fitted into a pod on each wing. This aircraft is the only transport flying now or probably will be for the next five years due to no funding by the German Government. Due to favorable flight tests, the DO-31 could be the first generation transport.

The flight test program conducted by NASA was in addition to the builders test program and consisted of 11 of the total 30 hours the aircraft has flown. Unlike most earlier VTOL aircraft tests, this test was done also under simulated IFR conditions. Seventy total approaches were conducted of which 15 were hooded. Lift engines were started on downwind taking about 20 seconds to get the lift engine in to flight idle. Deceleration was from 150 knots to 50 knots while on a 12° glide path final, then the aircraft was pitched up to hover and let down. This type of landing approach took approximately three minutes and due to the pitch up, unacceptable for commercial use.

Because of this composite type propulsion system the aircraft was found to have very good flexibility. It has good control stabilization but is disturbed in turbulance at 160 knots, however, with the lift engines running, it was again very stable. There were no cross-wind landing problems.

The DO-31 with a thrust/weight ratio of 1.4 will not hover but approximates VTOL, accelerating while climbing out at 4000 ft/min. Lift engines are used up to around 160 knots and shut down. Even though the aircraft and engines were found to be very reliable and the system extremely successful as far as a research vehicle, several problems were found. While hovering on vertical letdown, there was a large gas cloud and reingestion became a problem. The noise was unacceptable and ground erosion bad. The pilot was extremely busy during landing as there were too many levers to manipulate. There are four controls instead of the usual two. Some lever integration needs to be employed to simplify the control problem for the pilot. NASA study report on this test should be completed about September 1971.

> "Incidently, a Japanese delegation has visited Germany's Dornice as the opening move toward a coordinated vertical takeoff and landing aircraft program."[31].

Conclusions

Despite the relatively advanced state of jet-lift technology, the remaining problems of low-speed performance, noise, and ground-proximity effects require considerably more effort before commercial lift-jet transports can be developed. Composite propulsion systems promise the best cruise performance but advancements in pilot control is much needed. The lack of actual experience on this type of fixed wing VTOL aircraft is a prime problem.

Lift Fans

General

This section deals with the lift fan and its applicability to V/STOL aircraft. In this section the general lift fan concept and several variations of this concept are discussed. The XV-5A, a research aircraft utilizing the lift fan, is surveyed in detail and the flight test results are summarized. Some future concepts of V/STOL aircraft using the lift fan system are presented.

The Lift-Fan Configuration

The lift-fan principle is another variation on the concept of turbine engine vectored thrust. In the lift-fan system the hot gas from the generator is used to drive a fan. The airflow from the fan then supplies the lift needed to operate the aircraft in V/STOL flight.

The overall configuration of the lift-fan system is basically determined by the method employed in the transmission of power from the gas generator to the fan. The two major types of power transmission are the mechanical linkage type and the pneumatic linkage type.

In the mechanical linkage concept the hot gas from the gas generator is diverted by valves into a load turbine assembly. The load turbine assembly consists of an interburner, speed governor and load turbine. The interburner reheats the exhaust gas to increase the energy available to the load turbine. The load turbine provides the shaft horsepower to the lift fans through shafting. Two examples of geared lift fans and turbines are given in Figure 58.

Each fan assembly consists of a right angle bevel gearbox, lift fan, and thrust vectoring louvers. The gearbox provides the power transmission to the fan and provides the speed reduction necessary to allow optimum operating tip speeds for the tip turbine and fan. The lift fan consists of a set of inlet guide vanes and a single stage fan (rotor and stator assembly). The variable inlet guide vanes permit thrust modulation for aircraft control in the vertical flight mode. The fan assembly also incorporates an exit louver system which vectors the thrust to provide fore and aft lift thrust control and horizontal thrust for roll and yaw control.

In the pneumatic linkage scheme the hot gas is delivered to a turbine that is essentially a component of the fan. The turbine is either located at the hub of the fan or circumferentially around the tips of the fan blades. The patter turbine, called a tip turbine, is generally preferred because of its thinness. This allows the turbo-tip fan to be installed in areas of the aircraft where thinness must be preserved, such as the wing. Several different arrangements of the turbine and fan are shown in Figure 59.

In the pneumatic linkage concept the gas generator can either be located in the fuselage and the hot gas ducted to the fan locations or the gas generator and the fan are mounted in an engine-fan unit with no gas ducting. The in-fuselage mounted gas generator has been used on the XV-5A V/STOL aircraft and is being considered in larger V/STOL aircraft now under study. The engine-fan unit arrangement is also being considered for larger V/STOL aircraft of the future. The in-fuselage generator scheme is shown in Figure 60 and the engine-fan unit is shown in Figure 61.

The pneumatic linkage offers some advantages over the mechanical linkage for the lift-fan system. Although the pneumatic linkage is slightly heavier it is much simpler and therefore more reliable than the mechanical linkage. The mechanical linkage requires high-speed shafting and several sets of right angle gearing to achieve the same result as the pneumatic linkage. The pneumatic linkage will be studied in more detail in the next section.

In both mechanical linkage and pneumatic linkage the lift fan concept offers some advantages over other forms of V/STOL propulsion systems. The lift fan principle uses the same engines for both vertical and horizontal flight. This results in a reduction in weight of the aircraft. The thrust augmentation of the fan means the aircraft will not burn excessive amounts of fuel during vertical flight and will operate more efficiently in horizontal flight. This is because the gas generators can be optimum matched to the fans. The control of the aircraft through vectored louvers and the power concersion principle used in lift fans is much simpler. The overall simplicity of the lift fan gives the system a high degree of reliability and a wide range of installation locations.

Current Technology

The XV-5B aircraft utilizes lift fans to achieve V/STOL flight and at this time is the most advanced aircraft utilizing the lift fan principle. The XV-5B is the designation for the XV-5A after repairs and modifications had been performed. These repairs and modifications were the result of accidents during flight tests. One aircraft was lost and the other damaged. The modified aircraft is undergoing further testing.

The XV-5A is the product of General Electric and Ryan Aeronautical Company. General Electric is the prime contractor and developed the lift fan system utilized in the aircraft. Ryan Aeronautical is the sub-contractor and developed the airframe for the system. The XV-5A is shown in hover flight mode in Figure 62.

The XV-5A is a low-wing airplane with a high-mounted Tee-tail. Two engine intakes are on top of the fuselage aft of the cockpit. The design gross weight is 9,200 pounds with a limiting weight for VTOL operations of 12,326 pounds, including 4,650 pounds of internal fuel. The overall dimensions of the aircraft are shown in Figure 63. The fixed dimensions of the engines and fans on one hand, and the restrictions of military requirements on the other, imposed many design compromises on the aircraft. The side-by-side seating caused the maximum width of the aircraft to occur in the cockpit section rather than in the engine section. To avoid the problem of reingestion the engine intakes were located atop the fuselage. But basically it was the GE lift-fan geometry that defined many of the major dimensions of the aircraft.

The heart of the lift-fan system used in the XV-5A is the General Electric J85 gas generator. Two of these gas generators are employed in the system. These generators produce a total of 5,316 pounds of thrust.

Connected to each gas generator is a two position flow diverter valve. This is the mechanical device which is used to convert the system to the vertical flight mode or the horizontal flight mode. When the diverter valve is in the neutral position no diverting of the hot gas results and the gas flows directly through the valve and is ducted for exiting through nozzles located in the lower aft section of the fuselage. In this neutral position the aircraft would be in the horizontal flight mode. When the valves are in a diverting position all of the hot gas from the generators is turned downward 90° into vertical ducts. When the valves are in this diverting position the aircraft is in the vertical flight mode.

Each vertical duct is then divided into three horizontal ducts that run to the fan system of the XV-5A. This results in a total of six hot gas ducts connecting the fans to the gas generators when the aircraft is in the vertical flight mode. Four of these ducts connect the gas generators to the two main lift-fans. One main lift-fan is located in each wing. These four ducts provide cross-coupling of each gas generator to both main lift-fans. This ensures vertical operation of the aircraft in the event of a loss of one engine. Due to the characteristics of the lift-fan system the aircraft retains more than 60% of its designed total lift when operating on one engine in the vertical mode. The remaining two ducts run horizontally to the nose of the aircraft where they are connected to the nose pitch fan. The pitch fan is used for control purposes when the aircraft is in vertical flight and also produces a portion of the lift thrust.

The ducts are connected to the fans by the use of hot gas scrolls. The scroll distributes the driving gas around to the turbine nozzles. There are two scrolls on each main lift-fan in each wing and two scrolls on the nose pitch control fan. Each of these scrolls form an arc of admission to the turbine nozzles of approximately 84°. The turbine drives the fan to produce the lift needed to achieve vertical flight. The entire XV-5A propulsion system is shown in Figure 64. This propulsion system is integrated into the XV-5A airframe and the result is shown in Figure 65.

The XV-5A uses turbotip driven lift-fans. A cross section of this tip turbine drive system is shown in Figure 59. The heart of this tip turbine drive is the fan rotor. The rotor consists of thirty-six large fan blades which are driven by a turbine mounted on the blades outer circumference. The entire rotors for both pitch fan and wing fan are shown in Figure 66. The nose pitch fan has a diameter of 36 inches and the wing lift-fan has a diameter of 62.5 inches.

In operation, the rotor augments the thrust of the aircraft's gas generator powerplant by almost a factor of 3. The total thrust of the J85 gas generator is 5,316 pounds, but due to the thrust augmentation of the rotor the resultant lift is 1,860 pounds. From the pitch fan and 12,900 pounds from the wing fans. This gives a total of 14,760 pounds vertical flight mode. This augmentation leads to an aircraft lift-to-weight ratio of 1.6.

There are three other major sections of the XV-5A tip turbine lift-fan system. These consist of a front frame, a rear frame, and the exit louvers. The front frame provides the structural support for the fan and acts as the fan inlet. This inlet can be closed off by use of butterfly doors located on the top of the wing. The rear frame houses the exit stators for the fan and turbine and also provides structural rigidity. The exit louvers are mounted on the rear frame and serve the purpose of thrust vectoring and closure of the underside of the fan.

The nose pitch control fan is constructed in basically the same manner as the wing lift-fan above. The installation differs due to the change in mission of the pitch fan. The nose fan is used to produce lift, trim, and control forces in fan-supported flight. The inlet to the nose fan is provided in the upper portion of the nose. The hot gas and air from the nose fan is exited through the bottom portion of the nose. There are two doors in the nose of the aircraft that are pivoted to modulate the fan thrust for pitch control. The nose fan can be shut down during portions of the transition flight to provide better handling characteristics. This view shows the exit area for the nose fan and also the pivoting doors for pitch modulation. The exit louvers for the wing fans are also shown and directly above these the butterfly doors are in the open position to allow air to flow into the wing fans.

The exit louvers of the fan are the means by which the aircraft makes the transition from vertical flight to horizontal flight and back to vertical. During the transition phase from vertical to horizontal flight the exit louvers on the fans are vectored aft in stages. The range of thrust and lift during this transition is from 0 pounds static with 14,760 pounds lift to 8,400 pounds static with 7,200 pounds of lift. During the transition phase of flight the horizontal speed of the aircraft is increased to the level where the aerodynamic surfaces of the aircraft begin to produce lift. The aerodynamic surfaces become effective at approximately 50 knots. The maximum fan mode horizontal speed is 90 knots which is well in excess of the wing stall speed in the jet mode.

At the beginning of the aircrafts transition from horizontal flight to vertical flight the hot gas from the gas generator is diverted by the diverter valve into the ducts for delivery to the fan system. For the ducted fan system to be usable the fan system must have a rapid response to this conversion command. This response is shown in Figure 67.

Several areas of problems that exist in the XV-5A are being studied. The probability of reingestion has been decreased, but the problem still exists. Some solution to the problem has been found by using a nose high attitude during landing and lift off. The final answer may possibly be found from further studies on the optimum location of engine intake relative to the fans. The problem of noise must also be solved. The lift-fan is not as noisy as the direct-lift engine, but is still far too noisy to be operated in most commercial situations. The thinness of the fan reduces the possibility of absorbing the noise generated during vertical flight. The only areas which can be treated with acoustic absorbing are within the fan frame and on the exit louvers. Recent work has shown that significant noise reductions can be obtained by proper selection of the fan geometry. The ducting of hot gases through the airframe represents a potential problem should a leak occur in the ducts. The result is a "blow-torch" effect which would result in severe damage to any portion of the structure near the leak. The solution to this problem will be solved from studies on various designs of the ducting that can be used.

The XV-5A enjoyed many successes during its flight testing. Perhaps its major accomplishment was that it showed that the lift-fan principle is a very practical method of achieving V/STOL flight. The favorable results from the program can be found in future V/STOL designs.

Future Concepts

The lift fan is being improved so as to be applicable to future V/STOL aircraft designs. The tip turbine lift fan is drawing most of this attention. The lift fan will improve through fan design improvement, gas generator improvement and more optimum choice of fan size, pressure ratio and bypass ratio.

A second generation fan of the XV-5A fan has been built and tested. The fan utilizes some of the advances in lift fan technology and the results obtained are given in Figure 68. This shows that during a short time span considerable improvement in the lift fan was made. The size and weight of the second generation fan is lower and the lift nearly doubled.

The lift/cruise fan is a derivative of the lift fan concept. Its evolution from the lift fan is illustrated in Figure 69. The system can be used for lift and cruise by either rotation of the fan or by thrust vectoring. The major components of the lift/cruise fan are shown in Figure 70. Gas generator gas is admitted to the tip turbine through a manifold of ducts enveloped within a cowl defined by the high cruise speed inlet requirements. Tip turbine exhaust gas and fan discharge flow are controlled by a two position exhaust nozzle consisting of an inflatable rubberized fabric boot. The two positions of the nozzle are optimized for takeoff and cruise.

General Electric has built a demonstrator prototype of an 80 inch fan. This fan will be used as a large, offset, vectorable fan for lift and cruise propulsion of a V/STOL transport. This 8- inch rotor is presently installed in a lift/cruise fan test vehicle. The fan has a 1.3 pressure ratio and is powered by a close coupled J79 turbojet engine. The fan is designed to produce 27,000 pounds of thrust.

In many designs for future V/STOL aircraft the lift fan and the lift/cruise fan are used in combination for the propulsion system. A V/STOL transport model using this principle has a propulsion system that consists of two fold-out lift fans in the forward fuselage and two rotatable lift/cruise fans mounted Caravelle-style on the aft fuselage.

Another V/STOL transport model is shown in the VTOL mode in Figure 71. This model has two fuselage mounted lift fans, two wing mounted lift fans and two rotatable lift/cruise fans. The same model is shown in Figure 72 in the cruise mode. This is a high speed configuration applicable to 4 to 10 ton payload sizes. In this transport configuration, all fan systems are interconnected such that the loss of any single gas generator results in an evenly distributed 18% lift loss in a 4 engine, 4 ton transport and an evenly distributed 9% lift loss in an 8 engine, 10 tons assault transport.

North American Aviation has built a V/STOL transport model and the model has undergone testing in the NASA/Ames wind tunnel. The transport uses lift fans in the wings for vertical flight. The lift fans tested were 6 PGl fans, three in each wing. The PFl fan is the 36 inch nose pitch fan used in the XV-5A.

Another aircraft design using lift fans for V/STOL flight is proposed in Figure 73. This is a concept of a short haul V/STOL airliner. It uses 8 lift fans mounted in the wings and 8 wing mounted gas generators. The engine-fan configuration is identical to the one shown in Figure 59. The fan uses a portion of the airframe to replace the gas scroll and ducting. The proposed operation of the aircraft would include shut down of two or four of the gas generators during cruise so as to achieve optimum specific fuel consumption levels.

Another proposed design is shown in Figure 74. This design uses two lift fans in the nose, two engine-fan pods mounted on the wings and two lift/cruise fans mounted on the aft fuselage. The aft mounted lift/cruise fans do not rotate, but use instead a thrust deflector to give vertical lift to the aircraft. The aircraft uses two gas generators to drive the nose fans, one gas generator in each wing-tip and two gas generators for the lift/cruise fan. The gas generators are interconnected for reliability through hot gas ducts.

Conclusions

The lift fan has been shown to be a practical method of V/STOL flight. This was demonstrated by the XV-5A. Lift fan technology should increase during the near future to the point that large V/STOL aircraft could be built using the lift fan principle.

As with all V/STOL aircraft the problem that must be solved is the high noise levels generated by the fans. This area is on the verge of a large breakthrough and the problems associated with the noise levels will be solved in the years ahead.

The future outlook for lift fan V/STOL aircraft is unlimited. The lift fan system has potential application both in the close support and high performance fighter areas, and to medium and long range transports.

CHAPTER IV

TILT ROTOR-TILT WING VECTORED THRUST CONCEPTS

General

This section discusses V/STOL aircraft in the tilt rotor and tilt wing configurations. The basic concepts of both designs are essentially the same. Specific aspects of the two configurations, with their variations and examples of aircraft in those configurations, will be discussed separately.

There are three aspects to the basic tilt-rotor-tilt-wing concept. These aspects are:

(1) Vertical thrust provided by the propellers turning in a horizontal plane for take off and landing.

(2) Transition to and from level flight by rotating the propellers to a vertical plane.

(3) Same propulsion system used for vertical flight and cruise flight.

This last aspect, by avoiding redundant components, results in a substantial saving in weight. Contrary to the principle of using the same components for vertical and cruise flight, there is a variation from the tilt rotor configuration where the rotors do not provide the thrust for high speed flight. At a certain speed, thrust is provided by a fan jet and the rotors are folded and stowed. This variant will be mentioned again later.

In this section, the terms rotor and propeller will sometimes be used interchangeably. There is no well defined delineation between the two but, in general, the term used will have its usual connotation. Aircraft which fall into the tilt rotor category employ a tiltable mass flow generator that may or may not have the engine tilt with it. The mass flow generator may be either a rotor, a ducted or free propeller, a ducted fan or a turbojet or turbofan engine. Usual configurations for the tilt rotor class place the mass flow generator at the wing tips. If propellers or ducted fans are used they may be placed in a dual tandem configuration such as the Curtiss-Wright X-19 (Figure 75). When the tanden configuration is used, wing span can be considerably reduced [36].

There are a number of considerations in aircraft design common to both configurations. These are:

(1) Disk loading
(2) Recirculation of downwash
(3) Power and control systems

Disk Loading

A key consideration in V/STOL aircraft design is disk loading. An aircraft's speed is directly related to disk loading, as is downwash pressure and velocity, and noise. Hover capability, to include fuel consumption and efficiency, has an inverse relationship with disk loading. Since the method by which an aircraft obtains its lift for vertical flight determines the disk loading, one can see that the propulsion method chosen largely depends on the intended mission of the aircraft. Figure 76 shows the relationship between disk loading and hover capability for the different types of aircraft. This hover time considering respective efficiencies would represent a constant fuel quantity. Tilting rotors or props normally operate with a disk loading between 5 and 75 psf. Below 15 psf autorotation is possible [37]. The Bell XV-3, shown in Figure 77, which first flew in 1955 demonstrated successful power off conversions from cruise flight to autorotation [38]. Aircraft with disk loadings of 30 psf or more will be of the tilt wing configuration to avoid heavy loads on the wing in vertical flight.

The major factor that contributes to the problem of balancing hover performance with cruise performance is the thrust that is required. For example, an aircraft having a lift to drag ratio (L/D) of 10 indicates that cruise thrust need be only 1/10 of that required in hover. The best disk loading for a tilt wing/rotor aircraft is also influenced by the engine characteristics. The aircraft should have an engine where power required at take off is compatible with that required for cruise. If the cruise speed is low, the engine selected will be based on take off requirements and will operate at partial power in cruise. The result of partial power operation is high specific fuel consumption.

There are a number of concepts in development to ease this problem. One is a variable diameter rotor shown in Figure 78. Decreasing rotor diameter to 2/3 hover diameter at constant rpm would increase disk loading by a factor of 5 [38]. Another concept is to use a normal rotor for hover and low speed, with high speed capability being achieved by converting to turbofan thrust in cruise and stopping and folding the rotors.

Where CTOL aircraft have a L/D of 8-12 and a helicopter's L/D is approximately 4, a folding proprotor is expected to achieve a lift to drag ratio about 85% of that of a conventional aircraft for the same weight [39]. That loss comes from a 6-7% weight increase due to the additional machinery required and additional drag because of the nacelle housing the folded rotor. With the folding proprotor, the rotor is designed for optimum hover performance and the wing and fan jet engines are optimized for cruise. After the rotors tilt for forward flight and speed is increased, the rotor is slowly unloaded. At a particular design speed, the rotor can be declutched, stopped, and folded. With stowed rotors, speeds in the 400 knot range should be possible [40].

Recirculation of Downwash

Both configurations have common problems caused by recirculation of the downwash. However, the problem is much more severe for some aircraft than for others. Recirculation results in increased pilot workload in hover or low speed flight close to the ground; in some cases to the extent that stability augmentation is required. Passenger comfort is also a consideration in this area. In a tilting rotor configuration such as the XV-3, erratic rolling moments were experienced because of changing wing loads and loss of lift as circulation patterns changed. This particular problem was helped considerably by using large flap deflections in hover which also helped during transition [38].

Figure 79 shows typical recirculation patterns for the XC-142A. This aircraft experiences random disturbances below 25-30 feet with wing angles between 35 and 80 degrees. The downwash tends to roll up in front of the aircraft, resulting in the aircraft flying into its own downwash in forward flight. The effect is more severe as the aircraft approaches the ground and an accident early in the XC-142 test program was attributed to the recirculation [41]. Recirculation appears to be less of a problem in the CL-84 and disturbances do not seem to occur over a wheel height of 5 feet which is a propeller height to diameter ratio of 1.5 [42]. With the Curtiss-Wright X-19, a considerably different design, self induced lateral oscillations were excited. These oscillations were not predicted and made hovering close to the ground difficult without stability augmentation [38].

Power and Control Systems

The general arrangement of cross shafting for power transmission is fairly common to both tilt rotor and tilt wing configurations. Cross shafting and clutches are required to allow uninterrupted power transmission to all rotors/propellers in the event of engine failure. The same system permits some of the engines to be shut down in cruise flight to obtain better performance from the operating engines. Although the aircraft can stand an engine failure, they cannot, in general, stand failure of shafts, gear boxes, propellers, or propeller controls [20]. Figure 80 shows a typical power transmission arrangement for the CL-84 which will be discussed in a later section.

The method of aircraft control is also generally the same for both configurations. One major difference is that in tilt wing aircraft, aileron and flap deflections may be used for yaw control. Differential propeller pitch is a common method of roll control and for tandem configurations it provides pitch control. Fans, rotors, or jet exhausts may be used on the tail section to provide pitch and yaw control. Changes of pitching moments are kept to a minimum during transition by programming flap settings with wing incidence or different duct rotation rates in a tandem configuration such as the Bell Aerosystems X-22A shown in Figure 81. In cruise flight, most of the aircraft use conventional controls. Figure 82 shows the flap and wing programming sequence for the SC-142A. The control systems, for the X-22A and the Canadair CL-84, will be discussed in more detail in a later section.

Tilt Rotor Configuration

Performance

Because the helicopter set the example for VTOL aircraft, it seemed only natural that a rotor should be employed in the early attempts to give a fixed wing aircraft a vertical flight capability. The rotor provides the most efficiency in hover but the least in cruise flight. If a rotor blade is operated at its hovering rotational speed while in cruise, it is well below its optimum angle of attack. A reduction in tip speed of a proprotor to about one-half of hover speed lets propulsive efficiency approach that of a conventional propeller [43].

The Bell XV-3, employed a two speed transmission to reduce rotor speed by 40% for cruise flight [17]. A variable diameter rotor is being developed that will improve the propulsive efficiency in cruise flight by decreasing rotor diameter by some 40%. Work is also being done to develop variable twist or variable camber rotors. Bell Helicopter Company has developed a 25-foot proprotor which is expected to have good efficiency when used at speed of more than 400 knots [44].

Rotor and Propeller Dynamics

One problem of proprotors in tilt rotor or tilt wing designs is whirl flutter [45]. This is an instability due to interactions between rotor and wing dynamics. Whirl flutter is a spiral motion of the hub and may be in the direction of or opposite to regular rotor rotation. Rotor instabilities caused the crash of an XV-3 in October 1956. Normally, these instabilities are most severe at a particular high forward airspeed or occur during the tilting maneuver. Some of the steps being taken to ease the problem are the use of flapping restraints and stiffer blades, increased pylon mounting and wing stiffness, and swashplate-pylon coupling. Swashplate-pylon coupling is a technique which moves the swashplate when the pylon moves in such a way that makes the aerodynamic forces stabilizing rather than destabilizing. This technique is also known as focused rotor [46]. Use of composites in both blade and wing construction is also expected to provide structural damping [40].

The problem is not as prevalent in tilt wing aircraft as in tilt rotor for two reasons. First, the rotor or propeller in the tilt wing versions is of smaller diameter, thus, it is less flexible, and second, the tilt wing is usually stiffer so is more resistant to dynamic interaction.

Another problem found in rotors is that they are sensitive to gusts and maneuvering loads. Their reaction to these disturbances increase the pilot effort and decrease passenger comfort in flight.

Tilting Propellers

A tilt propeller is used as a compromise between hover and cruise performance. The Curtis-Wright X-19, a dual tandem configuration, employed propellers designed to produce a considerable radial force to produce additional lift during transition. This additional lift permitted the wings to be sized more for cruise. The shorter chord also resulted in less download from the propwash. These propellers were constructed of foam filled fiberglass for reduced weight. It appears that if propellers are to be used in future applications they will probably be in a tilt wing configuration.

A problem which was discovered early and still exists is the lack of data available on static thrust of propellers and the inability to accurately predict static performance of propellers. Hovering data for the CL-84 showed a deficiency of several per cent in static thrust [42]. Currently, accurate estimates are possible only through extensive testing [40].

Tilting Ducts

The major advantage offered by a tilt duct configuration is the ability to use a propeller of about 70% of the diameter of a free propeller [47]. There is also considerable lift obtained from the aerodynamic shape of the duct. These advantages must overcome the disadvantage of increased weight and increased drag due to the shroud and struts and countervanes. The tendency for stalls to occur over the duct transitions can also introduce undesirable stability characteristics. Figure 83 shows the Dak 16 (VZ-4) an early tilt duct configuration which had an 8-bladed fixed-pitch ducted fan on each wing tip. That particular aircraft experienced excessive longitudinal trim changes during transition [48]. That problem has been overcome in a dual tandem configuration such as the X-22A. The X-22A will be discussed in detail in a later section.

Tilting Jets

The Bell D-188A was a design concept for a Mach 2 fighter. It used a combination of rotating and deflecting lifting engines. Another aircraft which employs both rotating and direct lift engines is the EWR VJ-101. Other design concepts include combinations of rotating jets and other types of lift engines but it does not appear that an aircraft using only tilt jet engines is practical.

Bell Aerosystems X-22A

The X-22A shown in Figure 81 is a dual tandem ducted propeller research aircraft built by Textron's Bell Aerosystems Company. It was developed for the Navy managed portion of the Tri-Service V/STOL research program to prove the directed propeller concept. It is now being used as a platform for a variable stability system (VSS). The contract for the vehicle was let in 1962 and the first flight was March 17, 1966. The number 1 aircraft suffered severe damage after slightly over three flight hours in an emergency landing following a dual hydraulic failure. With the number 2 aircraft a development program of some 220 flights and 110 hours was completed.

The X-22A has a gross weight of 15,700 pounds, carries a crew of two pilots and has a payload of 1,200 pounds. It is powered by four GE T-58 1,250 horsepower turboshaft engines. Lift for vertical flight is provided by four interconnected rotatable ducted controllable pitch propellers. The ducts themselves also provide a large portion of the lift in conventional flight. Cross-shafting combines power from all engines to drive all propellers to provide safe operation in the event of engine failure. If an engine does fail, or is shut down, it is automatically declutched from the rest of the system. Eleven gearboxes are required to provide this cross-shafting.

A ground configuration change permits control of engine power by one of two methods; power control or pitch control. Power control is the primary method. In this mode propeller speed is controlled by a master governor control and power is controlled by a separate power lever for each engine. In the pitch control mode, power is controlled much the same as in a helicopter. Propeller speed is maintained by power turbine droop governing and power is changed with a collective pitch control.

The pitch control mode has quicker response to power commands but maximum speed is limited to 160 knots. Because of the slower response in the power control mode, altitude control in hover is more difficult but the aircraft can fly at high forward speeds in the same manner as an aircraft with a constant speed propeller.

Duct rotation is electrically controlled and hydraulically powered. Rate of rotation can be controlled by a "beeper" switch on the collective pitch stick or number 4 throttle. Maximum rate of rotation is 5° per second and the rate is reduced to one degree per second as the ducts approach the vertical or horizontal stops.

Aircraft attitude is controlled by appropriate combinations of propeller blade pitch and elevon angles. Gigure 84 shows the arrangement for pitch control in both hover and conventional flight. From that figure, the method of roll and yaw control is apparent. As the ducts are rotated in the transition from hover to forward flight the propeller pitch is gradually phased out of pitch and roll control by mechanical linkage and is phased to yaw control. Similarly, the elevons are phased out of yaw control into pitch and roll control. Rate damping is provided for all three axes by a dual stability augmentation system (SAS) to improve the flying qualities in hover, transition and low conventional speeds.

For take offs, ducts are positioned at near 90° and lift-off is accomplished by adding power and maintaining a level attitude much the same as with a helicopter. According to John W. Spencer, Bell Aerosystems' Chief Experimental Test Pilot, a steady hover is easy to maintain in ground effect and "when clear of ground effect, the X-22A is much easier to hover than present day helicopters." [49] In normal operation, duct rotation is used to control speed and the flight controls are used to keep the fuselage level. Vertical landings are made by holding the fuselage level and reducing power.

Take offs and landings can be made with any duct angle between 0 and 90°. Short take offs and landings are usually made with ducts at 30° for the best compromise between stability, handling qualities, and power required.

In transitions between hover and conventional flight, handling qualities are very good. The control stick is used for altitude control and duct rotation is used to control speed. There is quite a wide latitude of speeds available at any duct angle. For a duct angle of 60°, speed can vary between 20 and 60 knots. For 0 duct angle, speed can vary from 80 knots on up to the maximum speed of 220 knots. Duct rotation can be accomplished in climbs and descents so climbing departures and descending approaches can be made on the same manner as with a helicopter.

The X-22A is now being used as a research system with the variable stability system. The VSS permits pilots to experience a wide range of aircraft characteristics and evaluate various aspects of V/STOL performance and flying qualities. This will serve to help establish V/STOL handling criteria which are not clearly defined and investigate many areas yet to be developed [49].

Tilt Wing Configuration

The basic concept of the tilt wing configuration as stated in the general section also requires that the wing be immersed in the propeller slipstream. This makes it possible to produce lift at high angles of attack during the period of transition between vertical and horizontal flight. This is the deflected slipstream concept and has been used alone to produce vertical thrust. Figure 85 shows the Ryan VZ-3 which used the deflected slipstream concept alone. This concept did not meet with much success generally because of the high losses involved in turning the slipstream [50]. Also, a very heavy flap arrangement is required to be powerful enough to provide the slipstream deflection that is required. Another problem is the aircraft altitude required during vertical flight. In the case of Canadair CL 62-1, a 20° nose high hovering attitude was required to maximize lift [51]. The pilot disorientation from such an altitude results in less than the full capability of the aircraft being achieved.

On a tilt wing aircraft, a high wing is normally used. This provides for prop clearance for larger than normal propellers and a better cabin height. A high wing also provides better longitudinal stability [52]. The wing is normally pivoted near the 45% chord station.

In the tilt wing concept, there must be a compromise in wing chord size between that required for transition and optimum for cruise. A small chord would be desirable for cruise, however, in order to prevent separation during transition a large chord is required.

Because of the large angles of attack, during low speed, high rate descents as well as during transitions, high lift devices were found necessary to provide the needed slipstream deflection and prevent stalling. Figure 86 is a typical plot of the variation of airspeed with rate of descent showing the buffet boundary. This particular plot is for the CL-84. The problem in descents is further aggravated because of the reduced power which decreases slipstream velocity. The high lift devices normally used are full span leading edge slats and trailing edge flaps.

Most of the tilt wing aircraft have had good success in transitioning from a hover to forward flight. Figure 14 shows the configuration changes that occur during that transition with the XC-142A. Transitioning from conventional flight to vertical flight has proved to be more difficult.

Another factor which contributed to an aircraft's ability to resist wing stall is the number of propellers and their direction of rotation.

With four propellers it is impossible to avoid adverse propeller slipstream which increases angle of attack over a portion of the wing. With two propellers, where outboard tips are going upward, the affect of the slipstream toward the wing tip is less and local loading is smaller so there is less tendency to stall [53].

The propellers on the XC-142A were a significant advancement. They were fiberglass and foam around a steel spar similar to, but an improvement over, those of the X-19. The saving of weight contributed much to the success of the program. Sand erosion proved no problem because of a replaceable protective storp on the leading edge. Blade damage could also be repaired by a simple fiberglass patch [41].

The XC-142A had no reverse thrust. Because considerable use in the STOL mode can be expected, future aircraft of this type should have reverse thrust [41].

An advantage of the tilt wing over the tilt rotor is in low speed maneuvering. Since the prop or rotor must be tilted at low speeds, having the wing tilted keeps it immersed in the slipstream providing positive lift at all times.

An early version of a tilt wing aircraft, the Vertol VZ-2 is shown in Figure 87. This aircraft has played a major role in development of the tilt wing concept. Because of this long period of development, the tilt wing is the most advanced VTOL aircraft aside from the helicopter. It appears that the major limitations of the tilt wing aircraft may be a top speed of about 400 knots and, in commercial applications, public acceptance of propellers [54].

Both the LTV-Hiller-Ryan CX-142A (Figures 88 and 89) and Canadair Limited CL-84 (Figure 90) have undergone extensive testing and have shown the tilt wing concept to be feasible. Due, at least in part, to funding problems, both programs are now inactive. Both aircraft are very similar in concept but in their original design the XC-142A had a gross-weight of about 38,000 pounds compared to 12,600 pounds for the CL-84. Four XL-142A aircraft and four CL-84 have been chosen arbitrarily for further discussion in this report.

Canadair Limited CL-84

The CL-84 is a turn turboprop V/STOL aircraft using the tilt wing deflected slipstream concept. The aircraft was designed and built by Canadair Limited, a wholly owned subsidiary of General Dynamics. A general arrangement diagram is shown in Figure 91. The Canadian Government and Canadair contracted to share in the cost of its design and development in 1963. It was originally designed as a research vehicle but evolved to a development vehicle with military applications. It first flew on May 7, 1965 and made complete transitions January 17, 1966.

Testing was continued until September 1967. During that time the aircraft accumulated 405 operational hours including 305 flights with a total of 145 flight hours and a 20-hour U. S. Tri-Service evaluation. The program stopped in September 1967 when the single aircraft crashed due to a propeller control system failure. Since that time three CL-84-1 aircraft participated in military evaluations during 1970 by the Canadian Armed Forces.

The CL-84-1 has a vertical take off gross weight of 15,000 pounds and can be flown by one pilot. With full internal fuel and one pilot it has a payload of 4,200 pounds. It is powered by two Lycoming T53 1800 shp engines driving two 14 foot diameter 4-bladed, glass fiber and two 7 foot diameter coaxial tail propellers. Cross-shafting and over-running clutches are provided between the engines and propellers to guard against engine failure. This arrangement also permits one engine to be shut down in cruise flight for more efficient operation. A diagram of the propulsion system is in Figure 81.

The wing is hinged at the 45% chord station and is rotated to a maximum angle of 100 degrees by a hydraulic ball screw actuator. The surface of the wing is almost completely immersed in the slipstream and uses full span 10% leading edge Krueger-flaps and 30% trailing flaps. The wing chord is one-half the propeller diameter.

The horizontal tail is low to be below the wing wake in level flight. This position also keeps it always in the slipstream, thereby avoiding large changes in pitching moments with changes in wing tilt. There are three vertical tails to improve directional stability at intermediate wing angles. All flaps and the horizontal stabilizer are programmed automatically with wing tilt.

In a vertical take off, disk loading is 45 psf. The thrust to weight ratio of 1.07 for landing, 1.05 for hover, and 1.02 for take off [53]. These figures are about 0.03 less in all modes than for the XC-142A [41].

Unlike the SC-142A there is no collective pitch lever and power is controlled by a single power lever. This arrangement makes for very simple transitions between hover and cruise flight. This is made possible by the power lever being connected to the engine fuel control, but also at higher tilt angles, there is a scheduled authority over prop blade angle to provide immediate thrust response in hover and low speed flight.

To take off vertically, the pilot tilts the wing to the desired position, depending on wind and advances the single power lever. In hover, fore and aft stick movements govern pitch of the tail propellers to provide pitch control. Roll control is through differential propeller pitch and yaw control is by differential flap/aileron movement. Both yaw and roll control are introduced by conventional use of stick and rudder pedals. As the transition from hover to conventional flight progresses with decreasing wing tilt angle and increasing forward speed, a mechanical programming unit provides a smooth transfer of control between hover and conventional flight. As forward speed increases the elevators become more effective and the tail propeller has reduced authority until when the wing is fully down, the tail propeller is declutched and stopped in the plane of symmetry. During transition, longitudinal trim changes are slight because the center of gravity location is near the thrust axis in VTOL flight and near the quarter chord for level flight [51].

A full transition from hover to 100 knots can be accomplished in 10 seconds [55]. Transition in descending or decelerating flight to a hover from 125 knots takes 25 seconds and is slightly more difficult because of less energy in the slipstream [42]. The airplane is highly maneuverable and has a dash speed of over 300 knots.

With the wing set at 45 degrees the CL-84 can clear a 50 foot obstacle in about 500 feet while carrying roughly twice the VTO payload.

The aircraft handles well in a hover, experiencing only minor random disturbances at wheel heights of 2 to 5 feet. A stability augmentation system utilizing rate gyros in all three axes is used in hover and transition. There is dualized pitch control and an attitude gyro is used to sense pitch with respect to a present datum. The SAS is nulled completely in conventional flight.

Translations may be made fore and aft using either pitch or wing tilt. The latter seems to be easier [53].

Planned applications for the CL-84 include a utility transport, rescue aircraft, helicopter escort and close air support. Because of a propeller disk loading of approximately 70 psf and the high speed requirements, a variable camber propeller has been selected for the close air support aircraft. Use of advanced composite materials is also planned in future applications of the CL-84.

Conclusions

It seems apparent that the capability to produce and operate a satisfactory tilt rotor/wing aircraft exists. More interest and money are needed to stimulate the program. As was pointed out, a high price in payload (50%) is required to have a vertical take off capability. However, a very high performance STOL aircraft would require a VTOL type control system for low speed operations. Therefore, pilots may not take full advantage of the aircraft capabilities and operate well above minimum speeds. Because of the difference in payload, or power required, VTOL aircraft should be operated in the STOL mode where runways are available [56].

Some of the major problems to be solved are in rotor and propeller performance. Several areas of research show promise. Some of these areas are in high speed variable diameter and twist rotors and the folding and stowed rotor concept. The Air Force has shown their interest in this concept by going out with request for proposals to build two 350 knots 10-15,000 pound stoppage and stowed rotor aircraft. A study by Bell Helicopter Company says a 60 passenger, 60,000 pounds gross weight proprotor civil transport can be built. The study states

> "A brief assessment of the impact of technology shows that when the projected advancements in materials, engine efficiency and aerodynamics are realized, the capability will exist to accomplish the mission with half the gross weight or to improve payload range or system survivability characteristics without exceeding the basic gross weight." [57]

CHAPTER V

COMPOUND VEHICLES (WING AND ROTOR)

General

Compound aircraft configurations have come into being as an attempt to increase the upper limit of speed for this type aircraft. But, just what is a compound aircraft that sets it apart from the others?

Basically a compound helicopter is a VTOL aircraft which derives its primary hover capability from a rotor, and after a transition phase, achieves cruise lift from a conventional wing and forward thrust from other than the rotor.

This chapter will briefly review the development of the compound helicopter, discuss approaches to configuration problem areas, and project compound aircraft possibilities of the future.

Historical Development

The compound helicopter, hereafter referred to as "the compound", is a revival of the ancient configurations which never quite made it off the ground. The Russians perhaps prodded our interest when they set a new world speed record of 220 mph in 1961. The aircraft was a huge twin-rotor winged helicopter. (See Figure 92). The Army immediately launched a program to develop a high performance helicopter (HPH) with Bell Helicopter Company. A large gain in range and speed was demonstrated. Further tests unloaded the rotor in flight by means of a wing and auxuliary propulsion. The change allowed investigation of performance at high forward speeds. This stimulating success gave an early boost to the development of compound helicopters which by 1964 had achieved a test speed of 200 knots. An objective of this development was to secure knowledge of high-speed data for the Advanced Aerial Fire Support System (AFFSS), now designated the AH-56 (Figure 93) for the U. S. Army.

Compound Testing

Five programs were implemented [63]:

(1) Bell Helicopter Company's "teetering rotor with wing and auxiliary propulsion.
(2) Kaman Aircraft Corporation's servo-flap rotor with wing and auxiliary propulsion.
(3) Lockheed-California Company's rigid rotor wing and auxiliary propulsion (see Figure 94).
(4) Piasecki Aircraft Corporation's tail rotor/pusher-propeller compound (see Figure 95).
(5) Sikorsky Aircraft's flapping rotor with wing and auxiliary propulsion.

These studies have resulted in a rather comprehensive understanding of the compound type vehicle. Although the future gains in compound development are limited, the immediate capability of near term technology can achieve significant results. Present top speed is the 263 knots flown by the XH-51A [63].

The compound is a present fact, in VTOL state of the art, as attested by many foreign commercial craft among which are the Russian Mi-6, the British Fairey Rotodyne, and British European Airways aircraft. (See Figures 96, 97, 98).

The Lockheed Rigid Rotor Craft (XH-51)

The XH-51 can readily reveal much general information about the compound. In fact it appears that tests on this vehicle are continuing even though other aircraft are of a more recent vintage.

In exploring the maneuvering capability of the XH-51A compound helicopter, steady turns and symmetrical pull-up were performed at various speeds. A maneuvering envelope that was significantly larger than the previous envelope was achieved and is indicated in Figure 99. The maximum load factor of 2.8g was obtained at true airspeeds of 195 knots and 225 knots. The maneuvering envelope is significant in that it eliminates the low-speed stall limitations of fixed-wing aircraft and allows far greater loading and speed capacity of the helicopter. The wing is small since take-off wing lift is not required. Thus the wing of a compound can be greatly idealized to the narrow confines of cruise speeds. This is a major savings in weight, structure, and design complexity of sophisticated high-lift devices.

Test results indicate favorable points as well as problem areas as follows [63]:

(1) Significant gains in speed and maneuverability.
(2) Delaying compressibility effects on the advancing blade by reducing rotor rpm was unsuccessful due to self-excited rotor blade oscillation.
(3) Maneuver stability remained positive over the maneuver envelope but decreased with both increasing airspeed and load factor.
(4) Rotor overspeed occurred certain combinations of airspeed, load factor and collective blade angle.
(5) A quick method of decreasing wing lift is required to safely enter autoration at high speed.

A number of projects have been under investigation in order to remedy the problems indicated above. In addition, some rather innovative ideas have come about which may supplant the compound helicopter entirely.

Recent Developments

In the quest for increased speed, drag continues as a major obstacle. As the wing, in cruise flight, accepts 80 to 90 percent of the loading and the rotor in effect windmills, the rotor presence serves only to cause drag. Thrust must now come from some other source. But it is this increasing drag at high speeds which is a major obstacle. Two general solutions appear to be: reducing rotor length in flight and stowing the rotor entirely.

Variable Diameter Rotors

There are two concepts which may effect results by reducing the rotor diameter: the TRAC System and a strap system.

TRAC System. This rotor system, under development by Sikorsky Aircraft, retains the desirable features of a low disk loading rotor in hover while greatly reducing its disadvantages in high speed aircraft. The concept uses a jackscrew mechanism operated through differential gearing (see Figure 100), which reduces both blade areas and tip speed. In the compound application drag is greatly reduced and stability increased. This idea can also be extended to stowed rotor aircraft where the blade and hub moments are greatly reduced so that stability and control problems are minimized in the conversion [64].

In the compound, hover rotor tip speeds on the order of 700 ft/sec are maintained, however, high transonic advancing blade tip mach numbers (above 0.9) will occur at forward speeds in the neighborhood of 200 knots. Profile power and rotor drag increase rapidly with Mach number at these high values.

> "Reduction of rotor tip speed by decreasing blade length provides several significant advantages over the conventional approach of RPM decrease. From a design standpoint, maintaining constant or nearly constant rotor RPM eliminates the requirement for design of electrical systems, for which constant speed generators are desirable. In addition, airframe vibration may be minimized because the fundamental frequency of rotor to airframe excitation (blade passages/second) does not change. This permits the airframe to be designed for minimum response (detuned) at only one frequency." [64]

Additionally by concentrating the blade mass over a shorter distance the ratio of blade aerodynamic forces to inertial forces is reduced, resulting in improvement of blade flap stability at high advance ratios. Increased stability is a result of utilizing the short blade. Altogether, these benefits enable speeds of over 400 knots for compound aircraft so equipped [64].

Strap System (Bell Aerospace Systems, Inc.). This variable diameter system achieves the same result as the previous system however instead of a jackscrew, a thong of laminar straps is used. The system relies upon inertia forces to sling the blades into extended position, and retraction of the blades takes place by pulling on the straps (see Figure 101).

Jet Flap Rotor

The jet flap rotor is a very promising research item in rotor systems. The Lockheed-California Company is conducting a number of parametric studies to evaluate various rotary wing boundary layer control applications including the jet flap.

Elliptic sections and the jet flap, made successful control of lift and roll by aerodynamic lift control instead of the conventional mechanical blade pitch. This control ranged from high advance ratio to stopped rotor flight [65]. The decided advantage in lift capability of the jetflap rotor over the conventional version has certainly heightened interest. (See Figure 102 and 103). Increased static lift capability and increased capability for high speed flight are realized. The ability to generate very high lift coefficients eliminates the blade stall on the retreating blade, and thereby indicates a possibility of minimizing the retreating blade stall problem of conventional rotors. This capability is also beneficial in reducing the problems of vibration which result from blade stall. The basic efficiencies of pneumatic systems are significantly less than the conventional, mechanically driven rotor.

However, trade-off studies are being pursued to evaluate the superior performance capabilities and the ready possibility of reduced vibration which can result in significant reductions in maintenance requirements and increases in reliability. The possibility of utilizing such systems as these for producing near uniform loadings on the rotor is also being researched [64].

A pleasant surprise arising from the jet flap research is a significant noise reduction with this method in spite of the fact that there was no attempt to design against noise.

Hot-cycle Rotor System

This system uses the hot exhaust of a gas-producer to energize a rotor system. The gas departs the power plant, is transmitted through the hollow rotor blades and exits near the rotor tips via directed exits. (See Figure 104). The benefits from this type system involve greater reduced vibration, no transmission (a major mechanical marvel in a helicopter), fewer controls, lighter weight, and much less maintenance. Some problems involve cooling of the gases as they travel the blade length, and an increase in creep stresses and decrease of fatigue limits at high temperatures.

Vibration Control

Maintenance costs of helicopters have historically been higher with much of the expense due to design allowance for these induced stresses, additional wear and tear on materials, and short fatigue life on dynamic components and airframes. Efforts to locate a remedy are found in two answers to the problem:

Bifilar Vibration Absorber. Sikorsky Aircraft has developed a torsional bifilar vibration absorber which is mounted at the top of the rotor mast and acts to counter the flapping moment of the rotor system (see Figures 105, 106, 107). Improvements in passenger comfort levels are claimed to be significant [40].

The DAVI. Kaman Aerospace Corporation has developed a dynamic antiresonant vibration isolator (DAVI), a passive isolator which counteracts spring forces with inertia forces. "At the predominant excitation frequency of the helicopter, an anti-resonance is obtained that gives nearly 100 percent isolation." [66] The system employs tuned damper isolators separating the airframe from the rotor system (see Figure 108).

Stowed Rotor System

The ultimate in compound aircraft is perhaps the stowed rotor concept of which there are many versions (see Figures 109, 110). The idea here is to stop and then stow the entire rotor system, completely eliminating the drag problem in the compound types mentioned earlier. Such a concept involves the weight penalties and volume requirements of a system which is utilized during only a portion of the flight mission. However, the flight benefits which will accrue from the vertical flight capability, and particularly for those missions which couple extensive hovering time necessitating good hovering economy with high cruise speed requirements, make this concept attractive. Current research efforts are directed primarily toward establishing satisfactory control to meet the requirements of the starting and stopping cycle. It is obvious that to preclude excessive blade flapping and bending moments during these phases, and also to prevent divergence, it will be necessary to assure adequate blade pitch control.

The possibility of applying circulation control rotors to the stopped stowed rotor concept is being considered. (See Figures 111, 112). Advantages of such a move are obvious since the rotor can be of considerable smaller size and weight and thereby occupy less volume when it is stowed. Several other potentials such as the elimination of the transmission and the conventional mechanical blade pitch control system also accrue which may make this a desirable concept to be pursued [67].

Advancing Blade Concept

Although this concept is not yet envisioned in compound form, the Advancing Blade Concept (ABC) twin rotor helicopter offers so much as an aircraft system that it is worthy of mention here. The twin rotors are mounted co-axially and are counter rotating (see Figure 113, 114). This Sikorsky system attempts to eliminate the problem of blade stall by unloading the blade as it passes on the retreating side.

The problems of compressible flow on the advancing blade can also be alleviated by reducing the loading on the advancing side and carrying the load primarily in the fore and aft quadrants. Rotor balance is obtained by virture of the two elements of the counter-rotating system since the unbalance of each element is cancelled at the hub. This factor removes the need for cyclic blade pitch control to maintain rotor lateral balance [67].

Simultaneous lifting creates a smooth aerodynamic situation. Vibrations are reduced. Greater lift can be produced on the advancing blades, where the dynamic pressure is high, than on the retreating blades, where the pressure is low. The difference in lift results in the rotor rolling moment indicated on Figure 113. To produce and maintain this dissymmetry in lift, the blades must be rigidly attached to the hub to prevent resonant flapping or bending at the rotor frequency. (Such motion occurs on conventional articulated and hingeless rotors and tends to wash out the lift dissymmetry, causing a reduction in total rotor lift). In addition, the moments from each rotor must be equal and opposite so as not to affect roll trim. The total lift distribution both rotors is shown in the upper part of Figure 113 and is compared to that of a conventional single rotor where the maximum advancing blade lift is restricted by the lift capability of the retreating blade. The ABC lift distribution exhibits characteristics similar to those of a fixed wing aircraft in that the lift is symmetrical about the aircraft longitudinal axis [40].

As with fixed wings, the maximum lift of an ABC rotor increases with speed as shown in Figure 114. Here nondimensional thrust is plotted against forward speed for both an ABC rotor and a conventional rotor. The limiting condition governing the maximum velocity of a conventional rotor, assuming adequate power is available, is retreating blade stall, and for typical designs the maximum speed attainable is only about 160 knots. The greater lift capability of the ABC rotor allows operation at higher values of thrust, thus requiring less blade area, and allowing the maximum speed to be limited only by blade stress and/or power available [40]. It is evident that an infinitely rigid rotor not burdened with roll trim requirements could maintain constant dynamic pressure on the advancing blades by reducing rpm and thus avoid exceeding the drag divergence Mach number until the rotor was stopped. This, of course, implies potential helicopter rotor forward speed capabilities exceeding 500 knots [40].

Current testing (see Figure 115) and materials technology (shown in Figures 116, 117, 118) place the ABC aircraft within the capability of current production.

Conclusion

The future of the compound must lie with the whim of demand. The technology is here or close at hand. A few compounds of the near future are shown in Figures 119, 120, 121. The single most promising compound vehicle will be the ABC with a potential 500 knot capability. The low noise levels, high speed, and low downwash velocity make this concept ideal for the city center to city center system.

CHAPTER VI

CONCLUSIONS

Although specific conclusions have been included for each chapter, some general conclusions gained from the entire study are presented.

Getting started with an all purpose operating V/STOL system will definitely require government support through the Department of Transportation and possibly the military. This is based on a V/STOL market over the next 10 years of approximately 200 aircraft which will just support one model. However, a problem may exist in trying to integrate the military and commercial requirements into one model. The military would probably accept a propeller design because of efficiency but a propeller design would be questionable to the airlines because of a jet conscious public.

It appears that the V/STOL concept capable of meeting the requirements of a compromise may be in some form of a high lift wing device. This is evident, to some extent, in the United States by a recent NASA RFP for a final V/STOL design utilizing either; internally blown flaps, externally blown flaps, or augmentor wing. It is even more evident among the foreign countries with the exception of the English Harrier.

It appears that everything is pointing to a solution of metroflight operation by the 1980-1985 time period. We feel, based on the information obtained for this study, that a working V/STOL system cannot possibly be operational by 1980-1985 without some drastic change in the data to a hypothetical extrapolated feasibility curve. We feel that the primary reason for this is a loack of interest involved in solving the present problem of how to implement the required details in obtaining the 1980-85 V/STOL system.

APPENDIX I

Economic Aspects

No study in any detail can be complete without an investigation into the economic impact and the marketability of the product.

In a country like ours where the majority of all commercial travel is by air, it stands to reason that commercial aviation forms a very important part of the total economic structure. Yet, commercial air carriers show a profit only while performing their designed function, i.e., flying. Therefore, aircraft must be designed with emphasis on simplicity and reliability in order to increase net profits, regardless of the mission to be performed [68].

In recent years, commercial air has become more and more short haul oriented with over one half of all flights being less than 500 miles and with eleven communities accounting for more than one half of all passenger enplanements. The air lines must react to this growing need in the short haul market, however the means to accomplish this task will not be simple. Time is money to the airlines. More short haul traffic will mean more stops and more non productive time spent on the ground. Current inefficient methods for loading and unloading of both baggage and passengers must be improved upon. Travel time from downtown to remotely located terminals must be reduced. Time is money also to the business man. The executive's time is normally valued at three times his regular hourly wage for non productive business time spent in traveling. Representative travel times from Manhattan, New York to downtown Philadelphia (Figures 122, 123, 124) show current travel by air as compared to travel by bus, downtown to downtown. A 50% reduction in travel time results from the use of STOL transportation utilizing terminal facilities nearer to downtown and more efficient loading, even through the actual flight speed is much greater by CTOL. Figures 125 and 126 show favorable expected STOL productivity and utilization and operating costs [68,69]. The STOL market has been and is forecast to remain on the upswing in the United States (Figure 127). To reduce operating costs and increase net profits, the airlines and metropolitan areas must jointly construct STOL Ports in or near center city. However, this requires maximum efficiency in utilization of real estate. Some areas in current use may be capitalized upon, such as the bay area design in New York or the over the expressway design for Houston. That is, vast areas of real estate under single level development may be extended to double level development. Passenger loading must be sped up by use of multiple entrances to the aircraft while servicing may be hastened by modular refueling and refurnishing (Figure 128).

A STOL aircraft should have no more requirement to shut its engines down at a stop than today's busses at a corner stop [70,71,72].

Current and near future operations of such V/STOL operations are considered to be within the state-of-the-technological-art and economically feasible. By scientific exploitation of the market and by capitalizing on the commodity of time, significant steps can be taken into the V/STOL future [73,74].

APPENDIX II

Airworthiness Standards

The Federal Aviation Administration published a document August 1970, entitled, "Tentative Airworthiness Standards for Powered Lift Transport Category Aircraft." [75]

The purpose and scope of this document may best be explained by quoting the introduction contained therein:

> "Existing civil airworthiness standards cover two broad classes of aircraft: fixed wing and rotary wing. There are now emerging aircraft designs which use a wide variety of novel methods for obtaining lift and control from their engines. The existing standards will need to be modified or supplemented to make them appropriate for the novel design features and operating characteristics of these new aircraft.
>
> This document presents tentative airworthiness standards for study, trial application, and comment during the design and development of verticraft and other powered lift aircraft. The tentative standards are not regulations and are not a formal notice of proposed rule making. Pending the adoption of regulations of general applicability for these aircraft, their type certification basis will be Part 25 or Part 29 of the Federal Aviation Regulations, as modified or supplemented by Special Conditions issued for the particular design under Section 21.16 (Amendment 21-19).
>
> Because of the wide variety of novel features in these emerging aircraft and lack of experience in their certification and operation, it is not expected that these tentative standards will be appropriate for all designs. However, the tentative standards should provide useful guidelines for designers and the FAA in arriving at the acceptable level of airworthiness. Appropriate rule making will be undertaken when sufficient knowledge and experience have been gained to provide a sound basis for adopting regulations of general applicability.

The tentative standards were originally issued in July 1968. They were the result of recommendations received from the Aerospace Industries Association, and subsequent discussion of an FAA draft at a public conference held 2-5 April 1968. It was noted at that time that the tentative standards would be revised from time to time and fully coordinated with interested parties. A public conference was held 21-23 April 1970 for the purpose of considering the need and nature of revision and updating of the standards. This issue, dated August 1970, reflects the changes which resulted from the 21-23 April 1970 public conference." [74]

Airport Planning and Design Criteria

Recommended criteria for the planning and design of STOL Ports in metropolitan areas is summarized by the following quotation from the introduction to FAA Advisory Circular No. 150/5300-8.

"The advisory circular outlines the basic physical, technical, and public interest factors which should be considered in planning and establishing metropolitan STOL ports. The information is based on STOL aircraft performance and research studies conducted by both industry and Government.

The criteria provided are advisory in nature and do not establish requirements except where Federal funds are used for the development of a STOL Port. Further, the specific recommendations presented are for the average or usual situation and may not be appropriate in every case. To assist in the interpretation of the criteria, it is recommended that technical advice be obtained from appropriate industry representatives and FAA technical personnel. Through consultations, the community can be assured of professional assistance in developing a STOL port that is safe, efficient, and compatible with its environment." [76]

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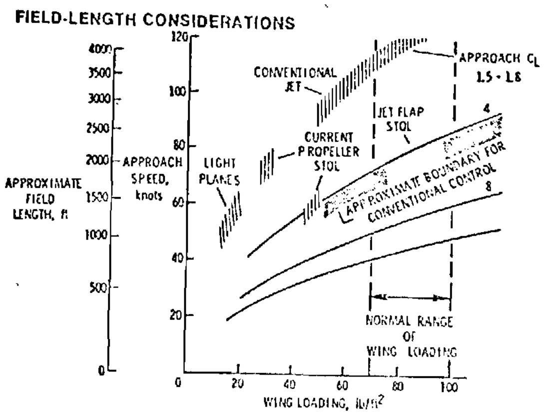

Figure 1. Field Length Considerations

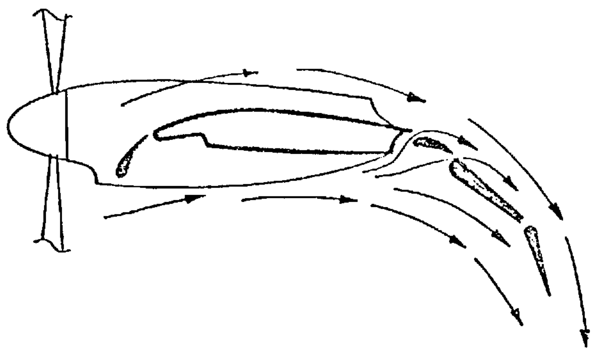

Figure 2. Deflected Slipstream Geometry

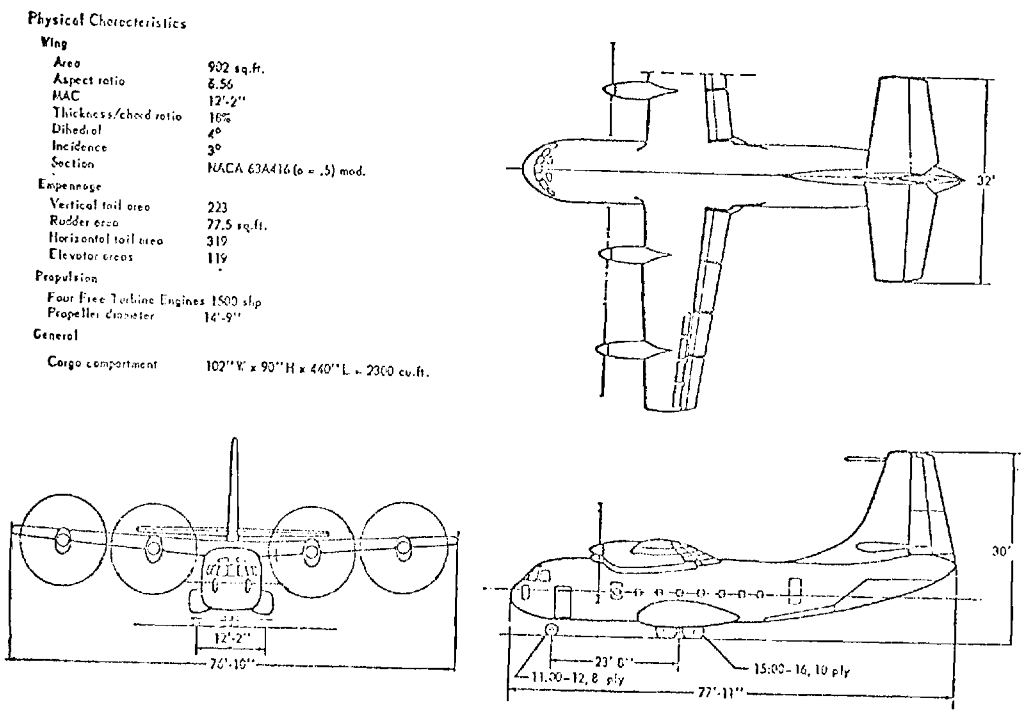

Figure 3. Breguet 941S/McDonnell 188E

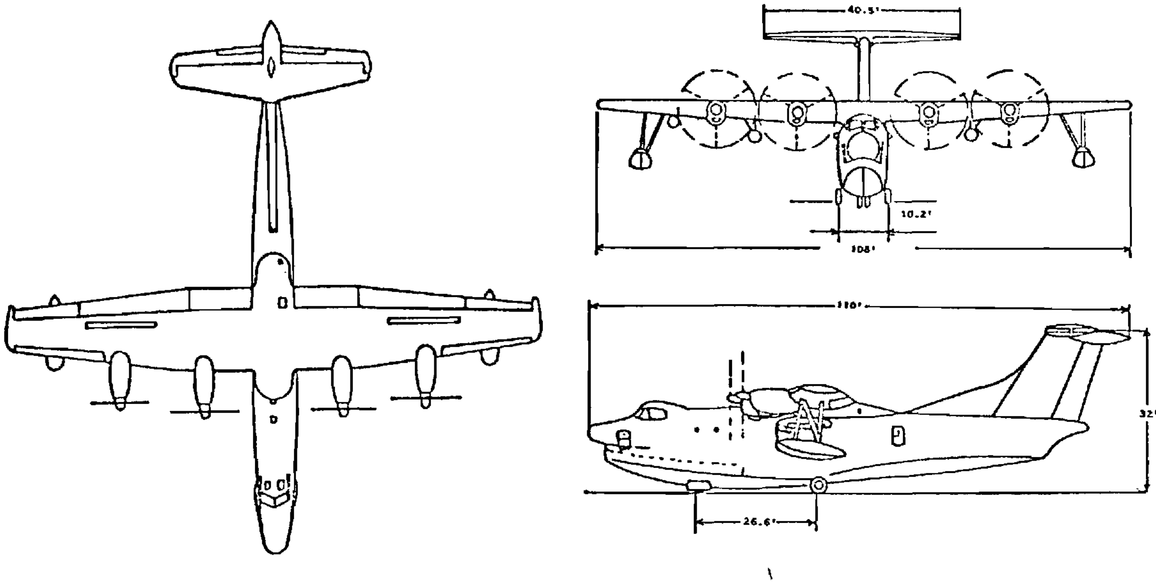

Figure 4. Japanese PS-1 STOL Flying Boat

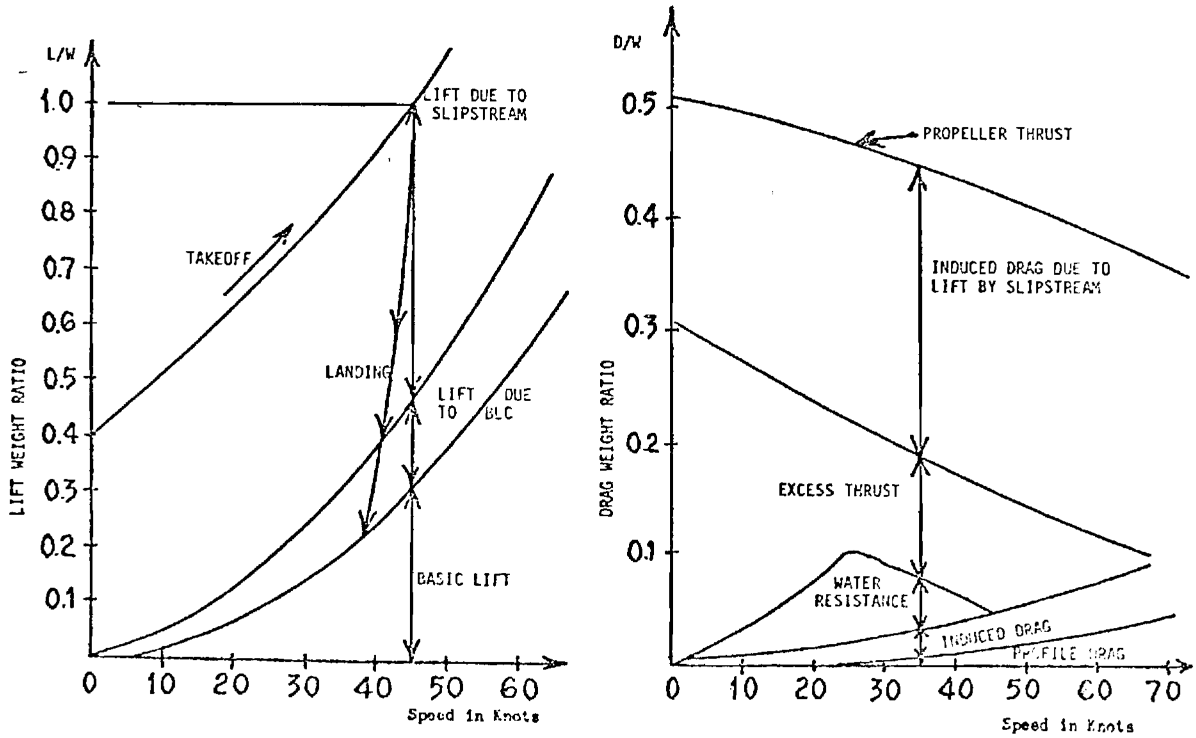

Figure 5. PS-1 Lift-Drag Weight Ratio vs Airspeed

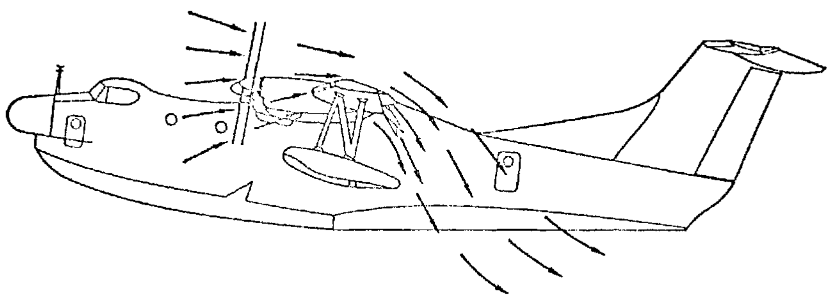

Figure 6. PS-1 Air Flow In STOL Configuration

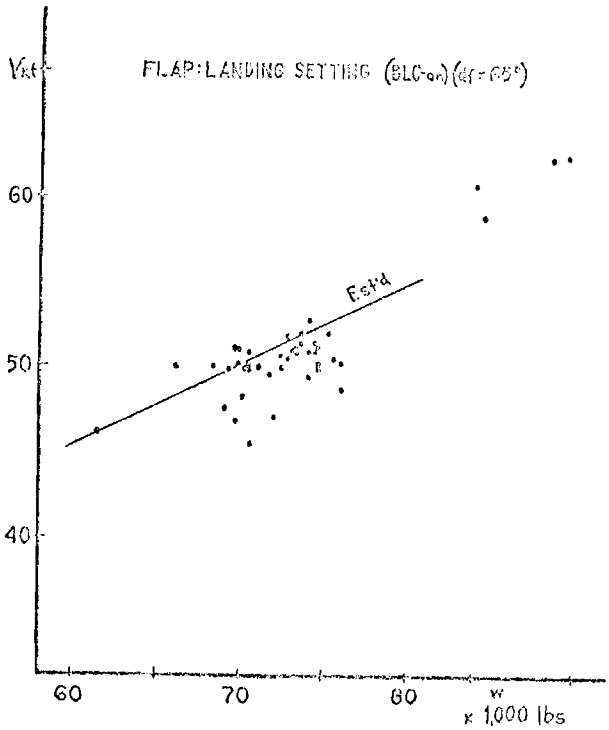

Figure 7. PS-1 Landing Performance

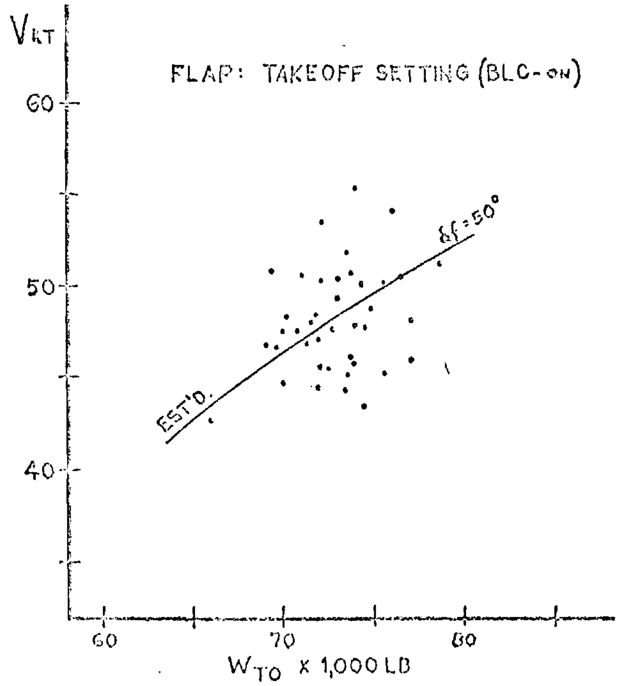

Figure 8. PS-1 Take Off Performance

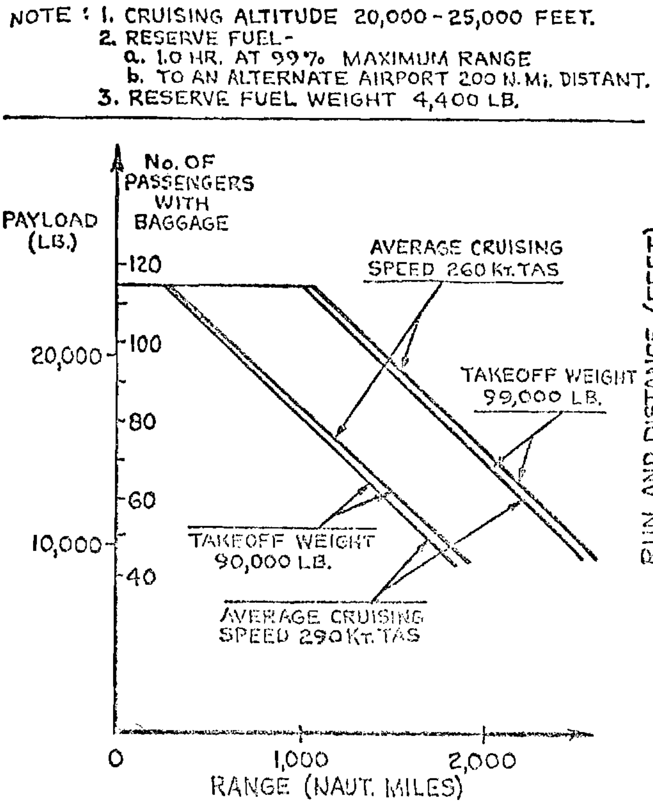

Figure 9. PS-1 Estimated Landplane Take Off & Landing Performance On The Ground

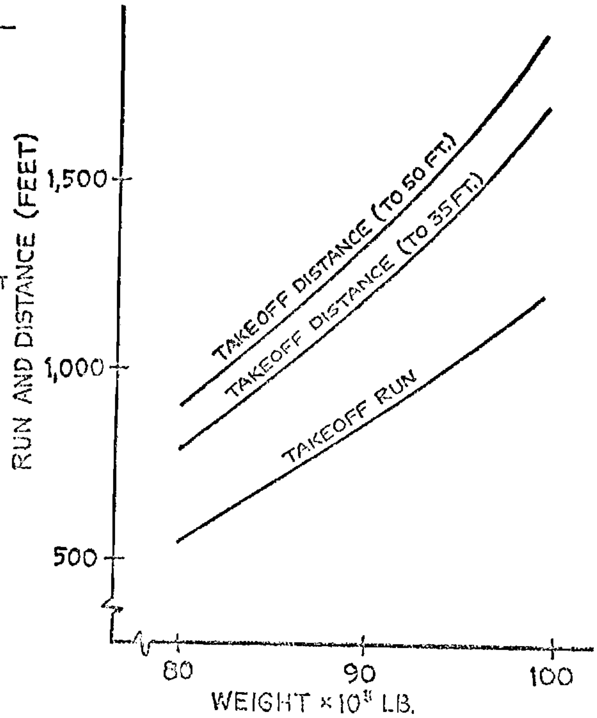

Figure 10. PS-1 Commercial Amphibian Payload Range

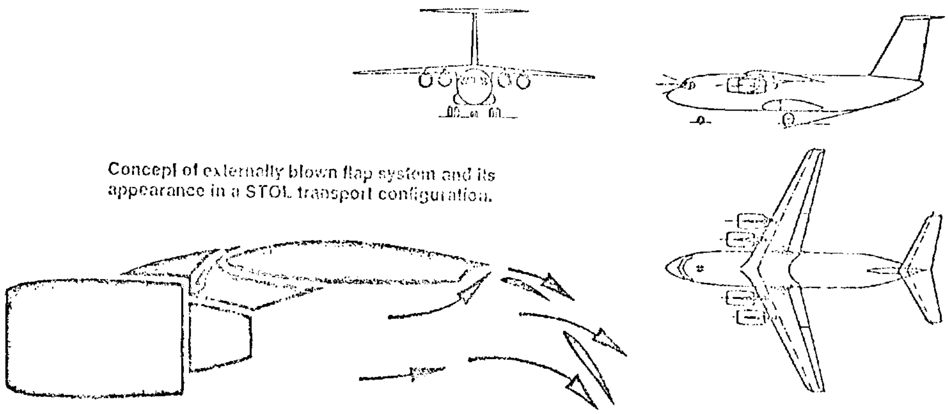

Figure 11. Concept Of STOL Transport Externally Blown Flap System

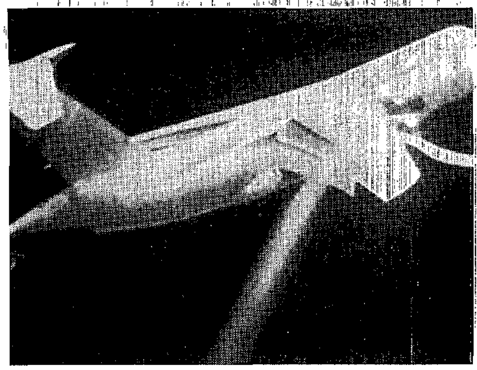

Figure 12. Externally Blown Flap Model

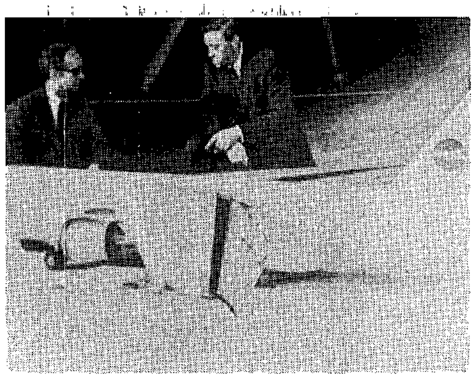

Figure 14. NASA Model Externally Blown Flap

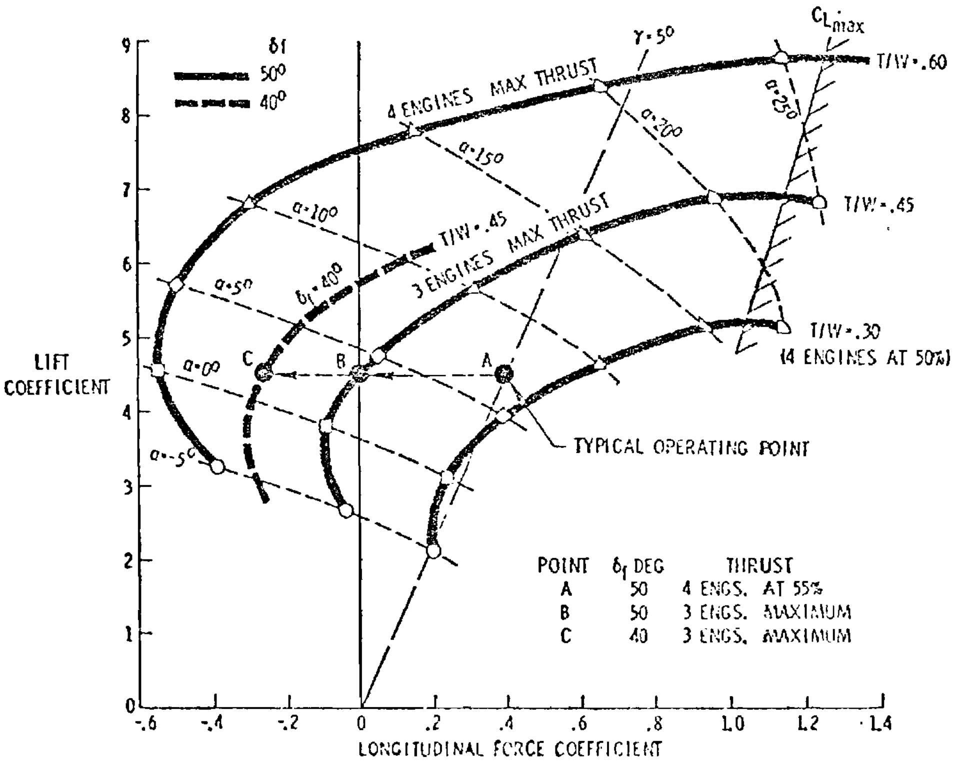

Figure 13. Landing Approach Configuration Performance

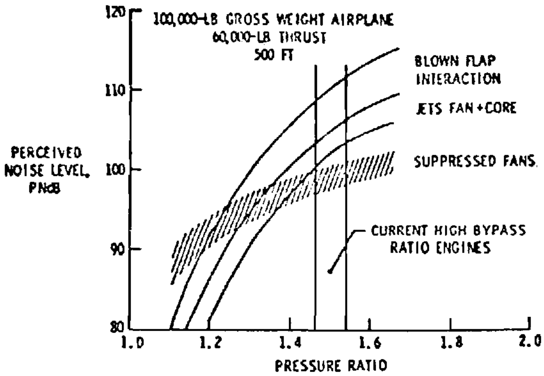

Figure 15. Noise Level vs Pressure Ratio For 100,000 Pound Gross Weight Airplane

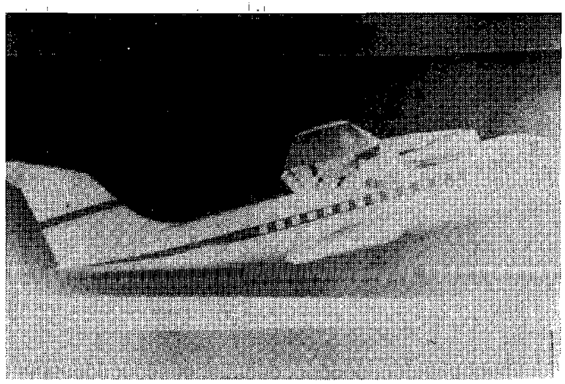

Figure 16. Bertin Aladin 2 Turbofan Blown Flap Model

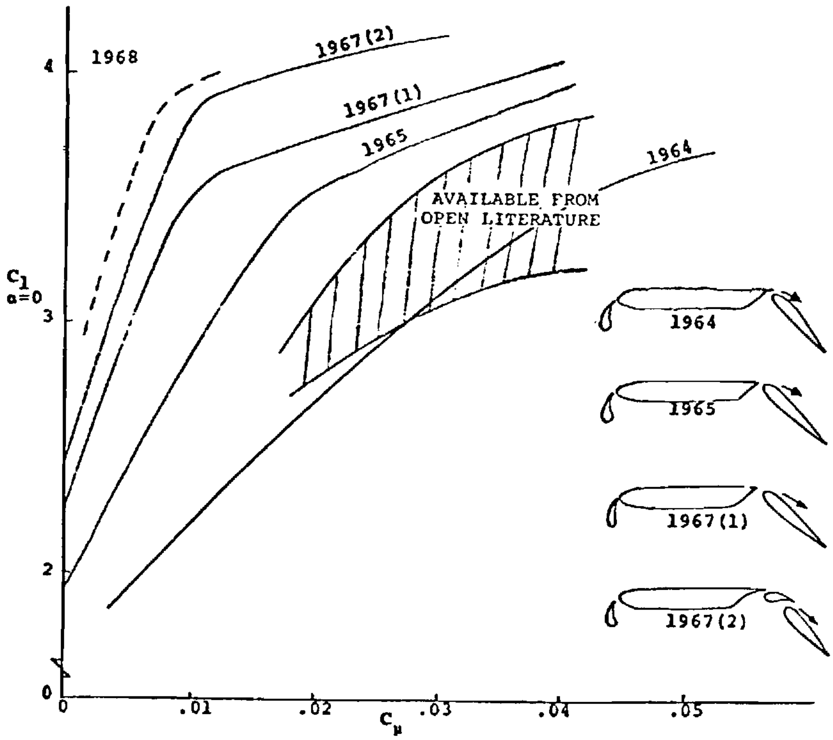

Figure 17. BLC Flap Effectiveness

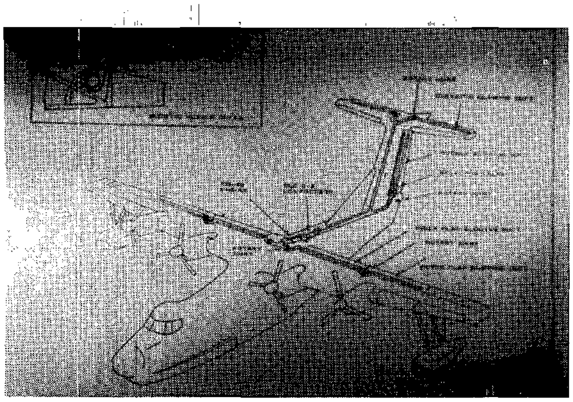

Figure 18. PS-1 BLC System

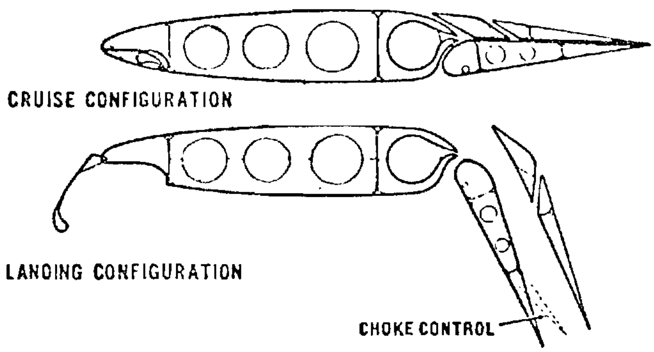

Figure 19. Augmentor-Wing Section

Figure 20. XV-11A External View

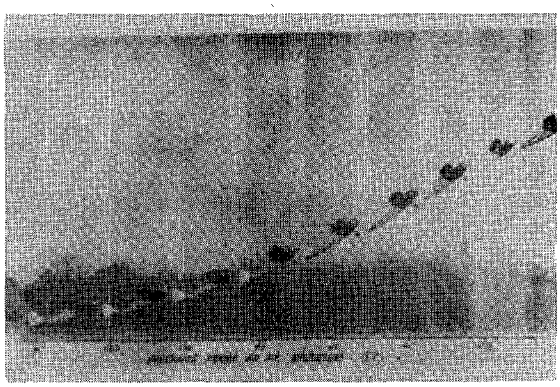

Figure 21. L-19 Take Off

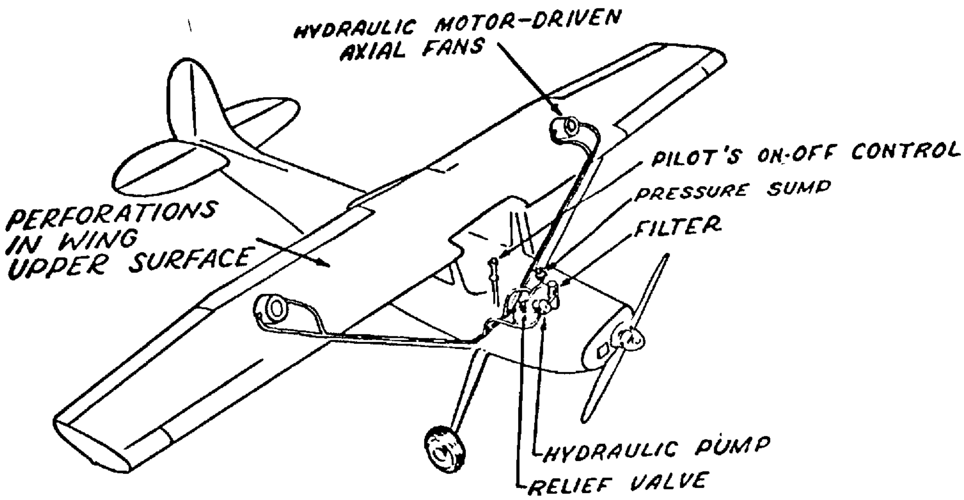

Figure 22. L-19 Schematic of Boundary Layer Control

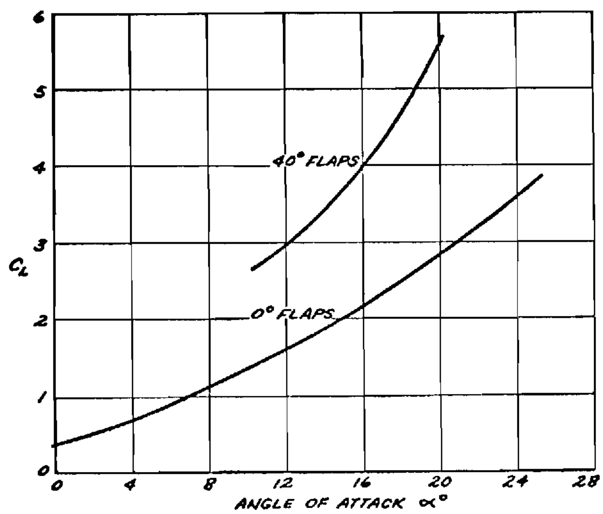

Figure 23. L-19 Lift Coefficient
vs Angle of Attack

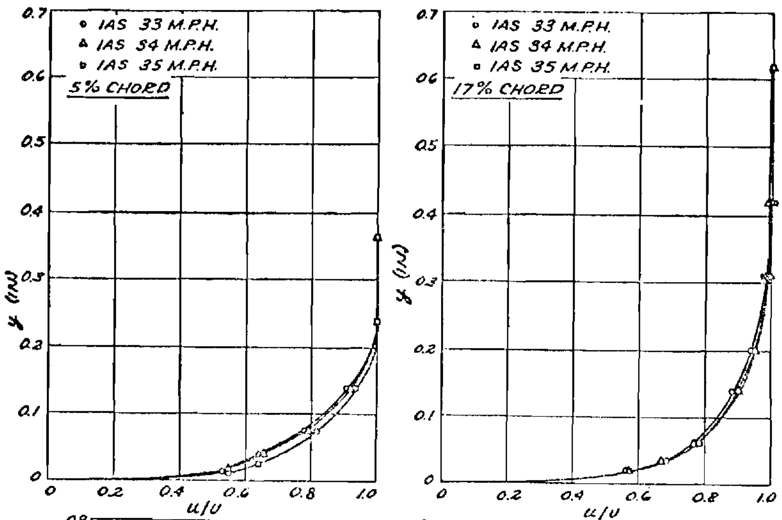

Figure 24. L-19 Profiles
Full Flaps

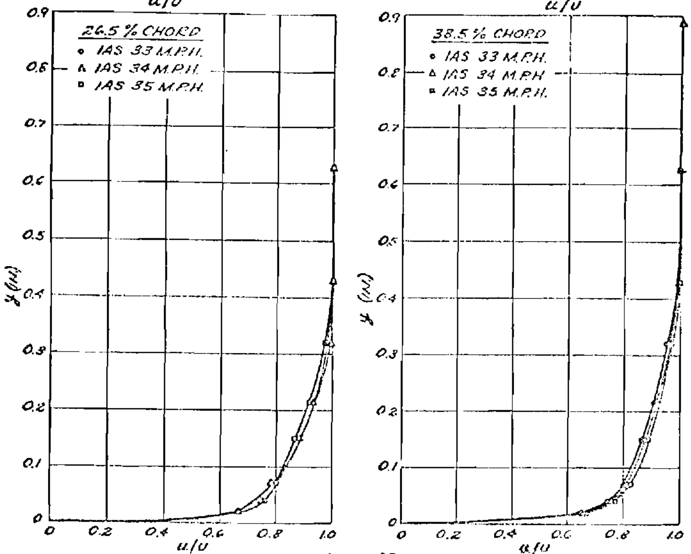

Figure 25. L-19 Profiles
Full Flaps

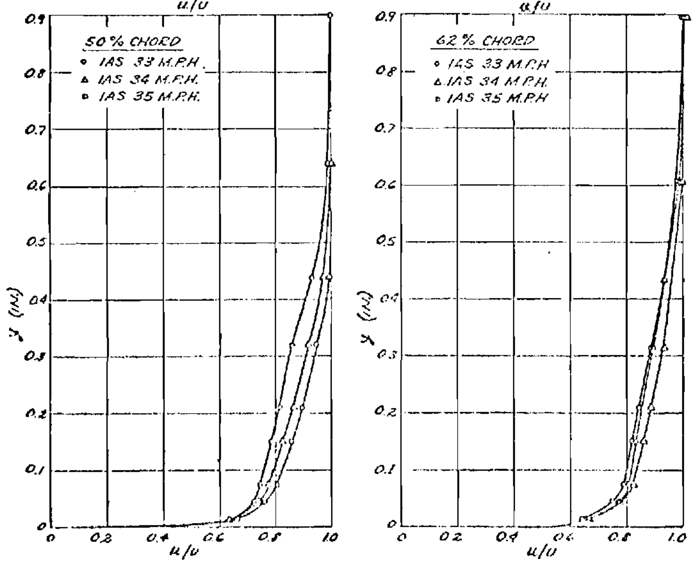

Figure 26. L-19 Profiles
Full Flaps

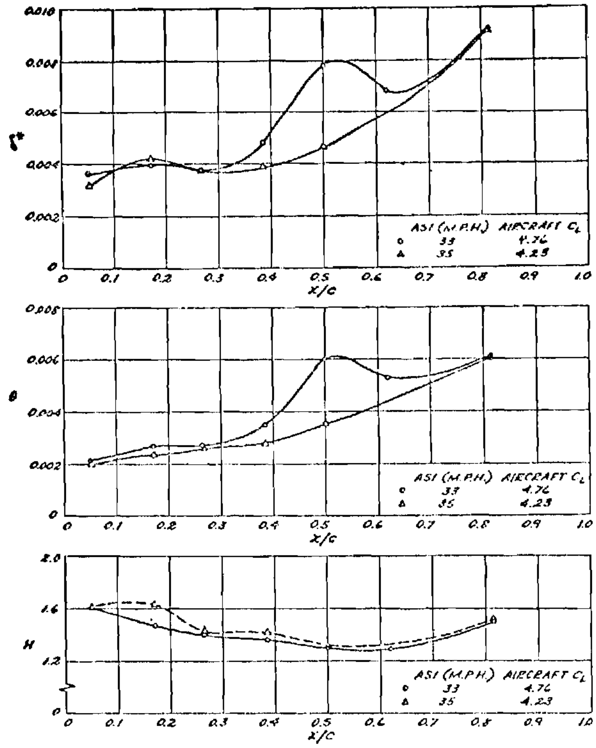

Figure 27. L-19 Boundary Layer Parameters

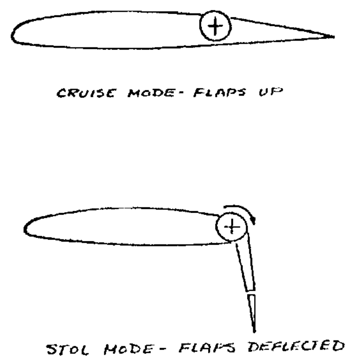

Figure 28. Rotating Cylinder Flap Concept

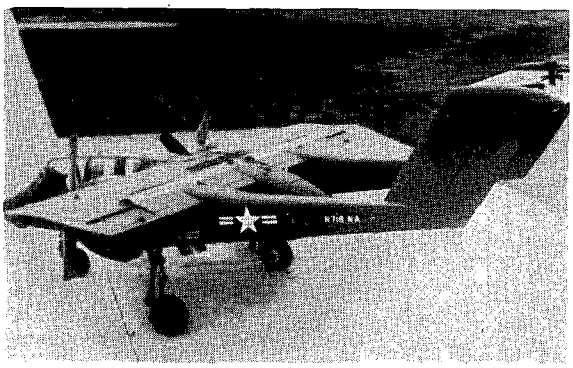

Figure 29. OV-10 STOL Flaps Up

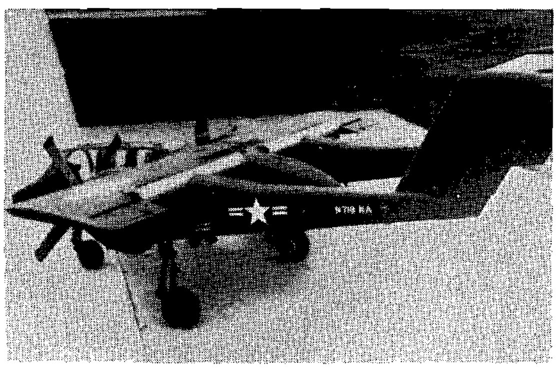

Figure 30. OV-10 STOL Flaps Down

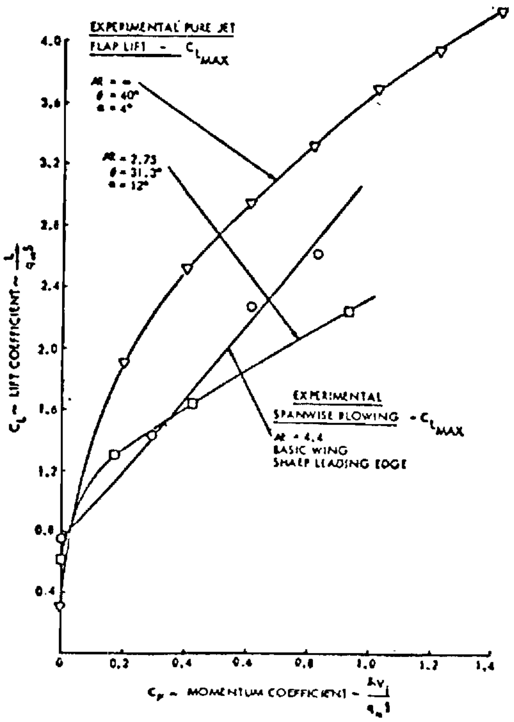

Figure 31. Comparison of Spanwise Blowing With Pure Jet Flap

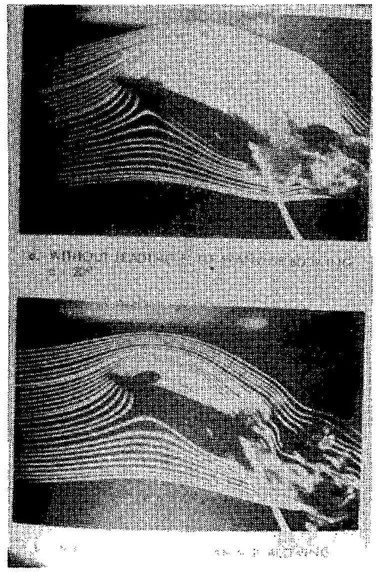

Figure 32. Control Of Separation Caused By Trailing Edge Jet Flap

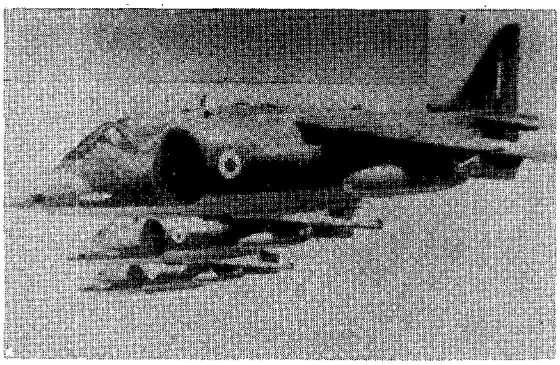

Figure 33. Hawker Siddeley Harrier

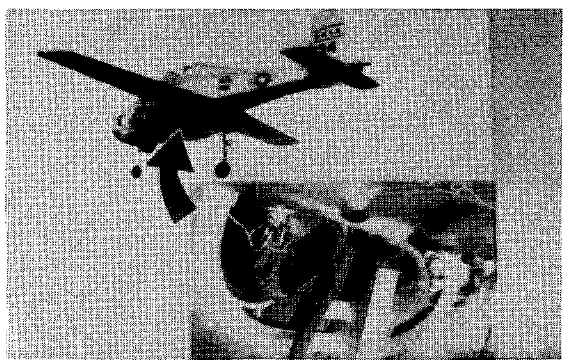

Figure 34. Bell X-14A

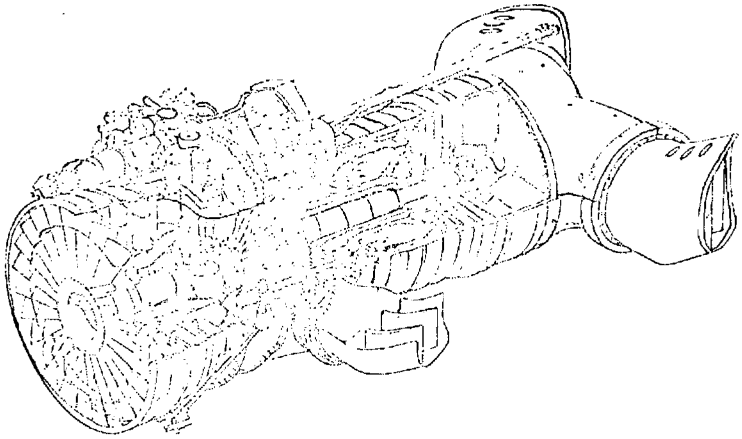

Figure 35. Rolls Royce Pegasus Mk 101 Engine

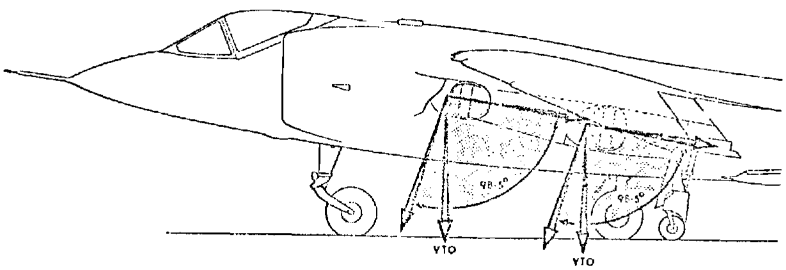

Figure 36. Harrier Thrust Vectoring Range

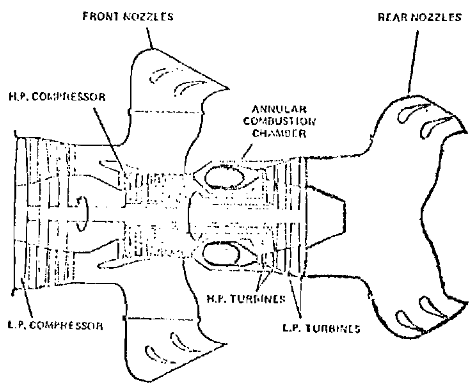

Figure 37. Pegasus Gas Ducting

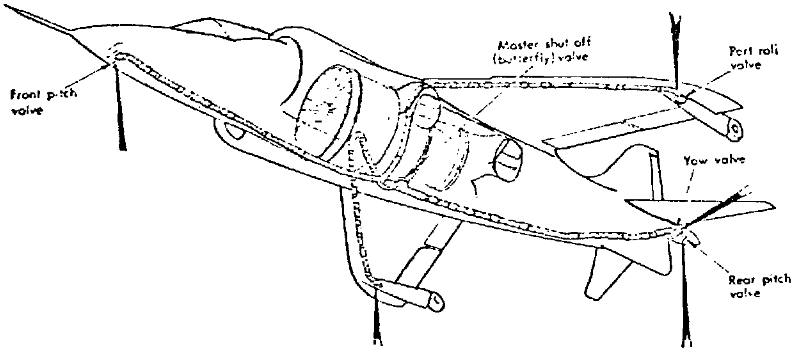

Figure 38. Reaction Control System

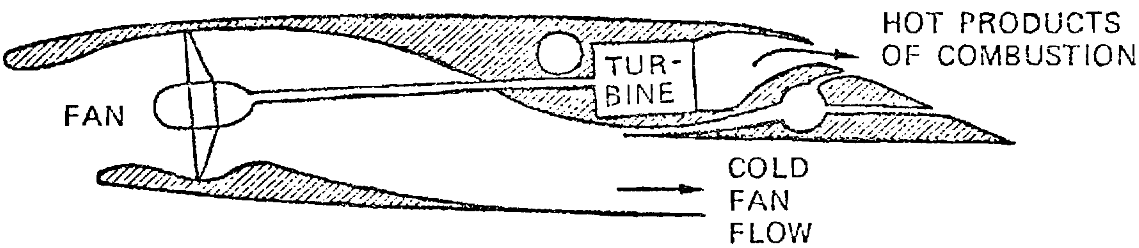

Figure 39. Propulsive Wing Section

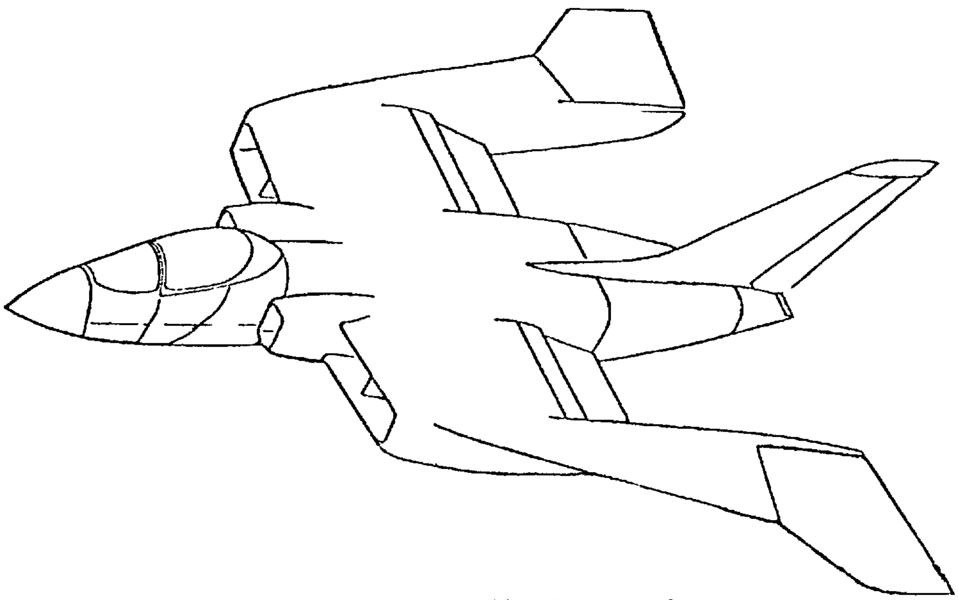

Figure 40. Small Strike-Recce Airplane

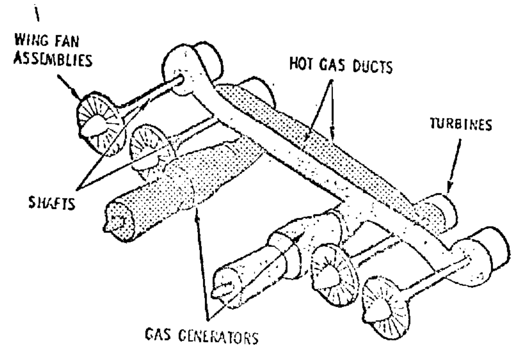

Figure 41. Propulsive Wing Propulsion System

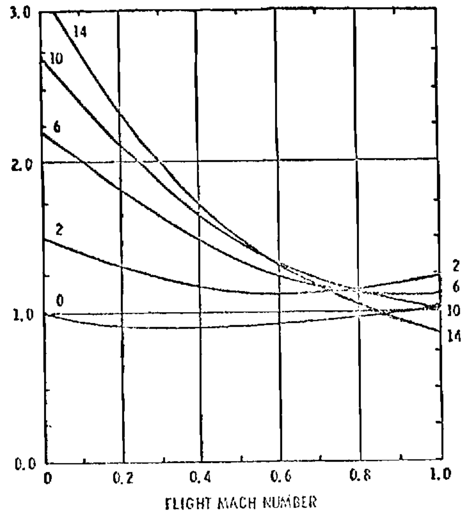

Figure 42. Effect Of Bypass Ratio On Net Thrust At Sea Level

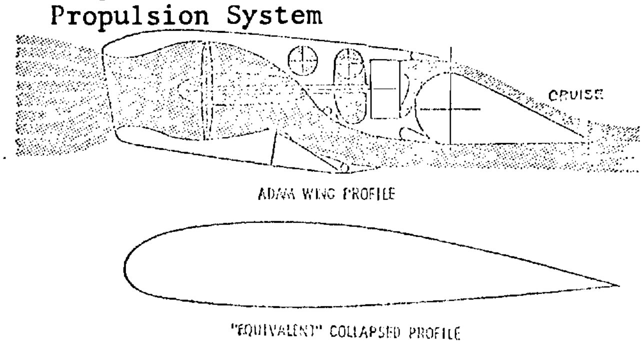

Figure 43. Collapsing Wing Profile By Removing Tube Of Propulsive Flow

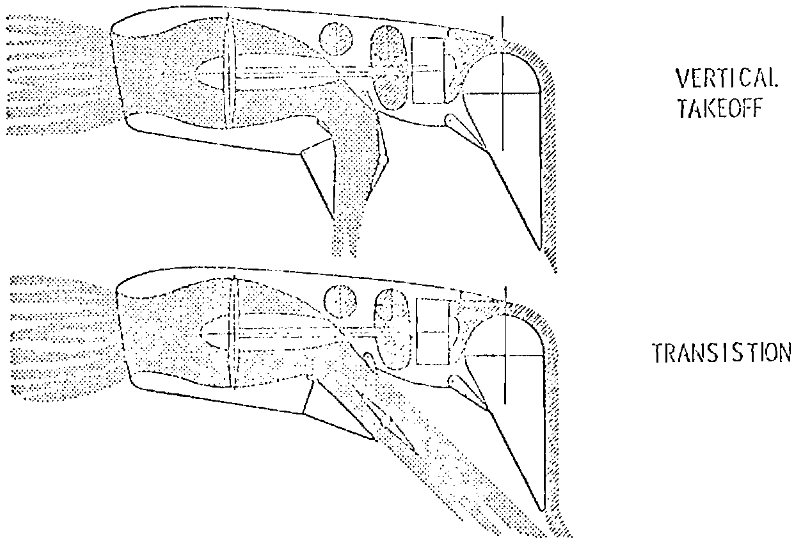

Figure 44. Thrust Vectoring

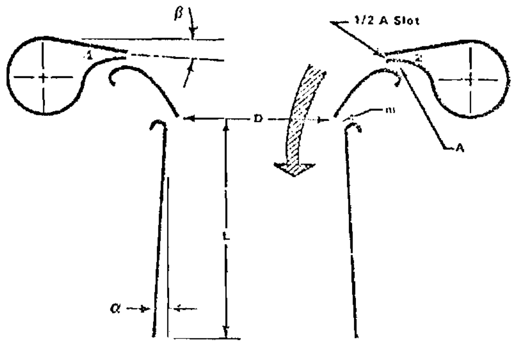

Figure 45. Coanda Nozzle Effect

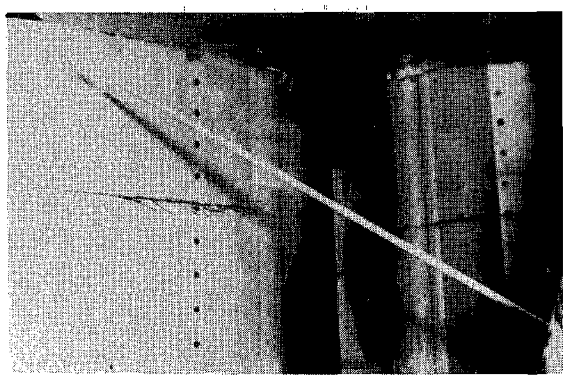

Figure 46. Coanda Nozzle Test

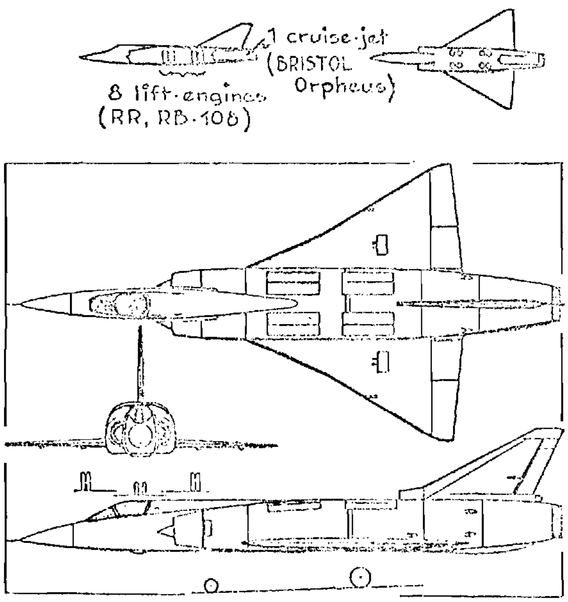

Figure 47. Mirage III-V

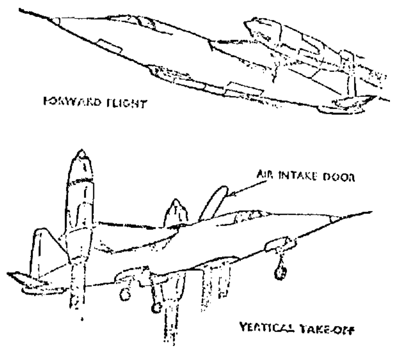

Figure 48. VJ 101C

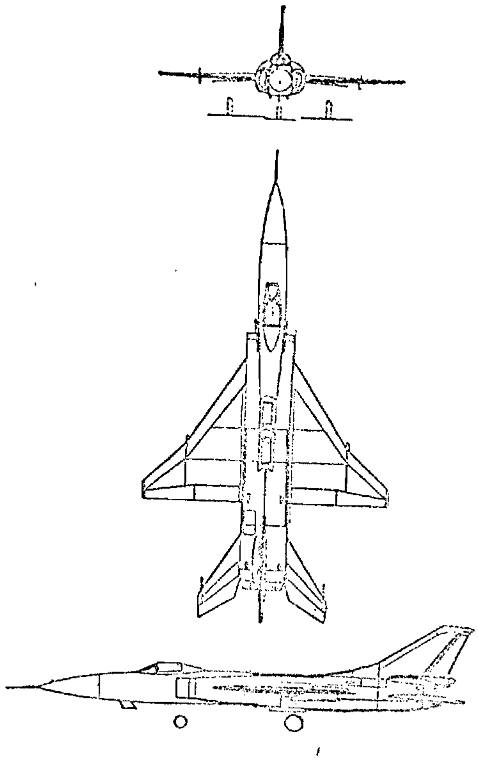

Figure 49. Flagon "B"

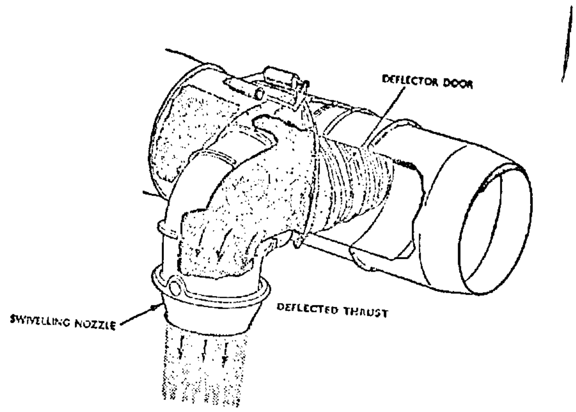

Figure 50. Deflected Lift/Cruise

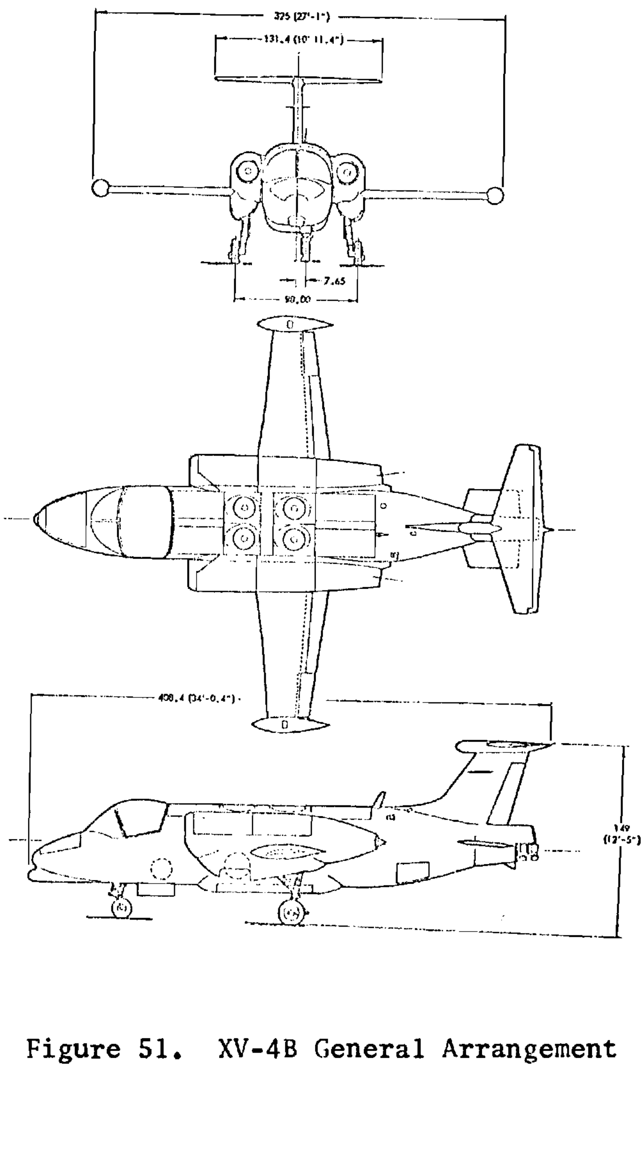

Figure 51. XV-4B General Arrangement

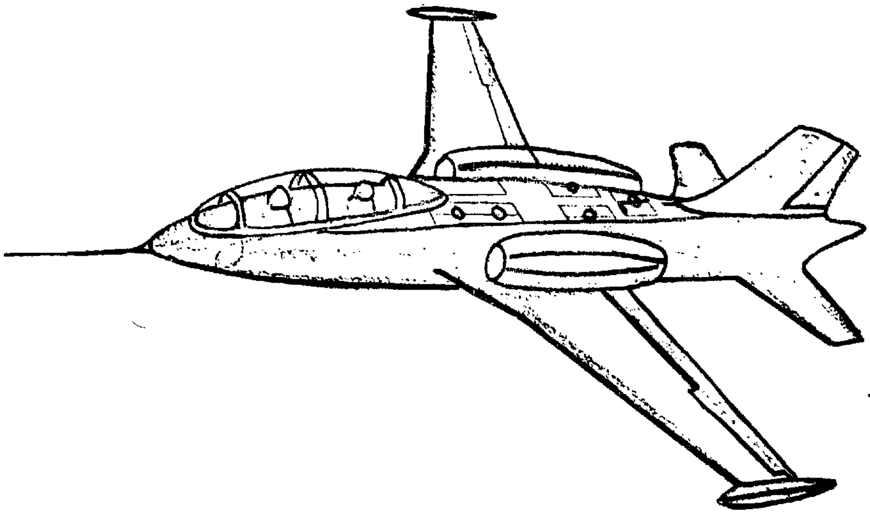

Figure 52. NASA Research Vehicle

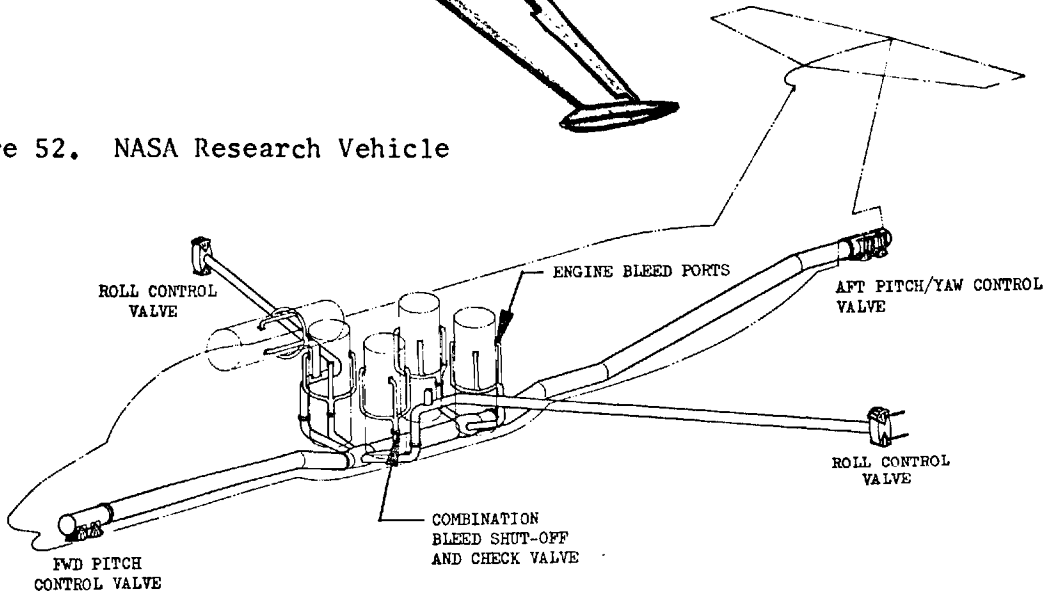

Figure 53. Reaction Control Bleed Air System

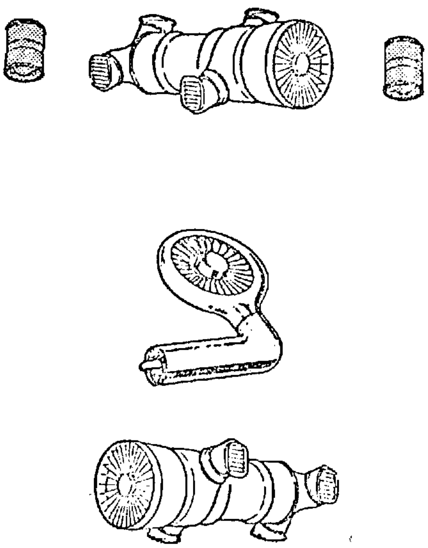

Figure 54. Vectored Lift/Cruise Plus Direct Lift

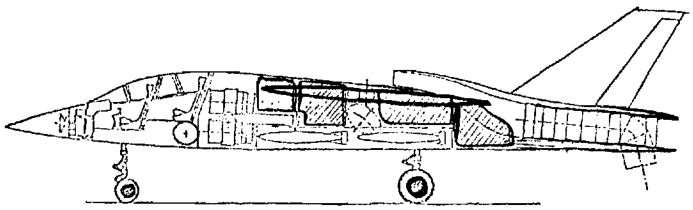

Figure 55. US/FRG Strike Fighter

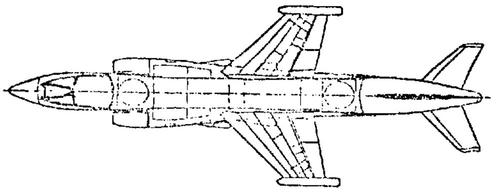

Figure 56. VAK 191B

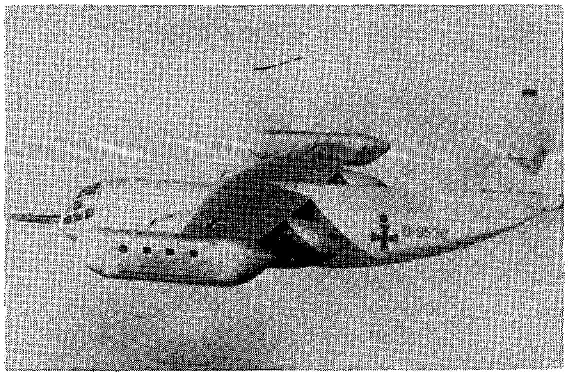

Figure 57. DO-31 Aircraft

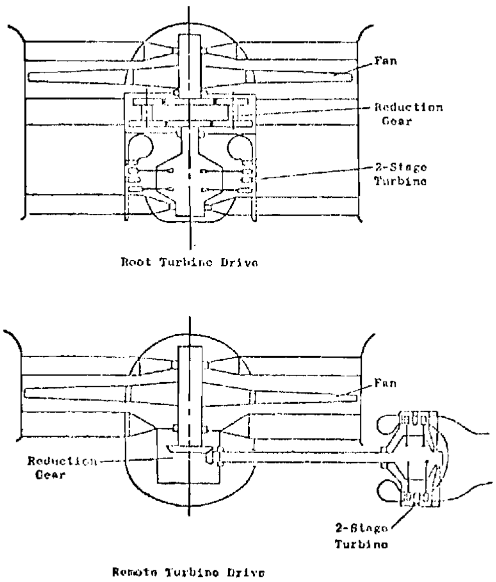

Figure 58. Geared Lift Fans

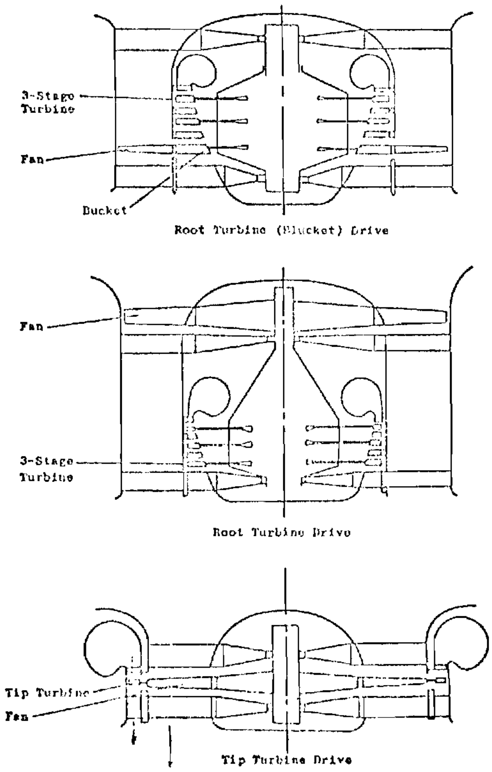

Figure 59. Pneumatic Lift Fans

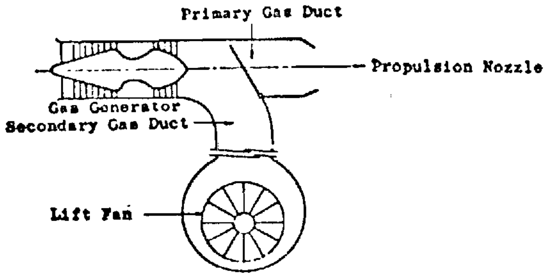

Figure 60. Lift Fan Jet Propulsion

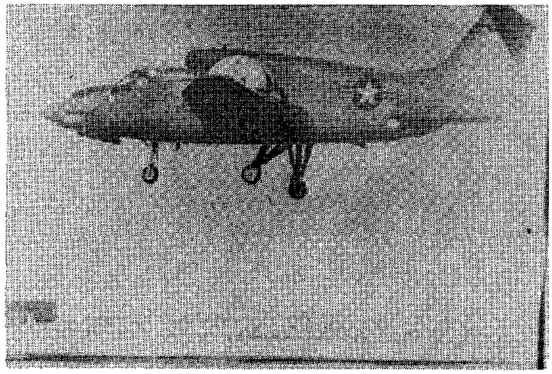

Figure 62. XV-5A Hovering

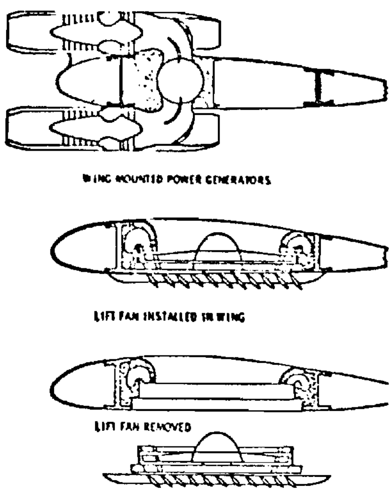

Figure 61. Lift Fan Configuration

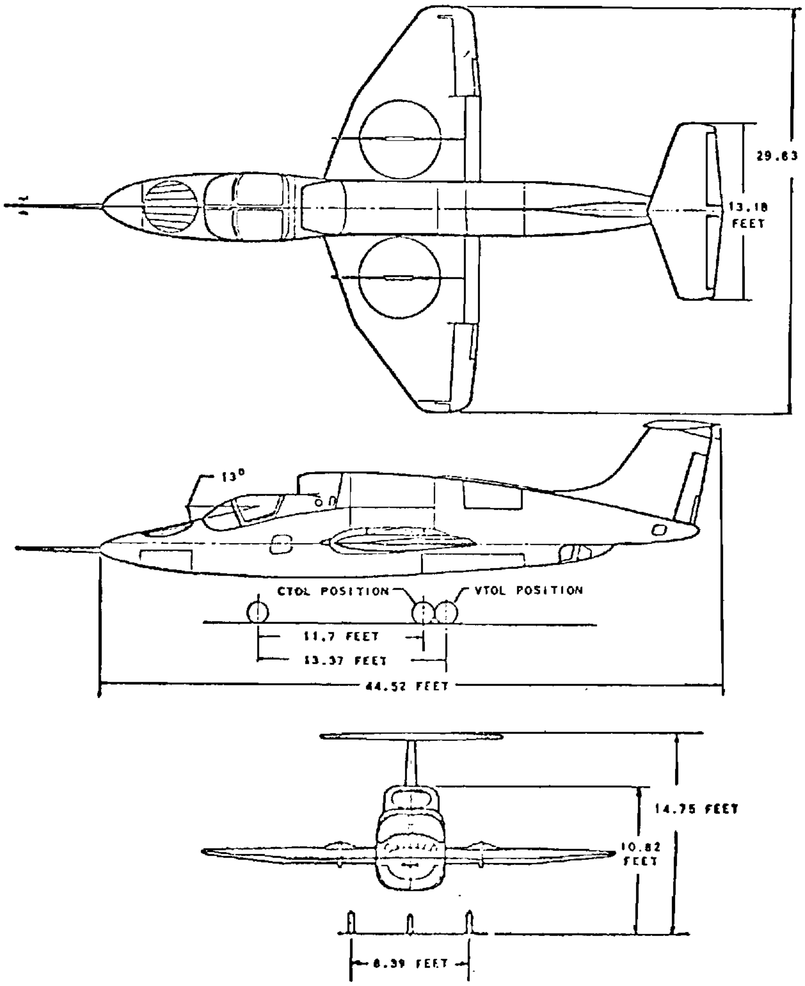

Figure 63. XV-5A General Arrangement

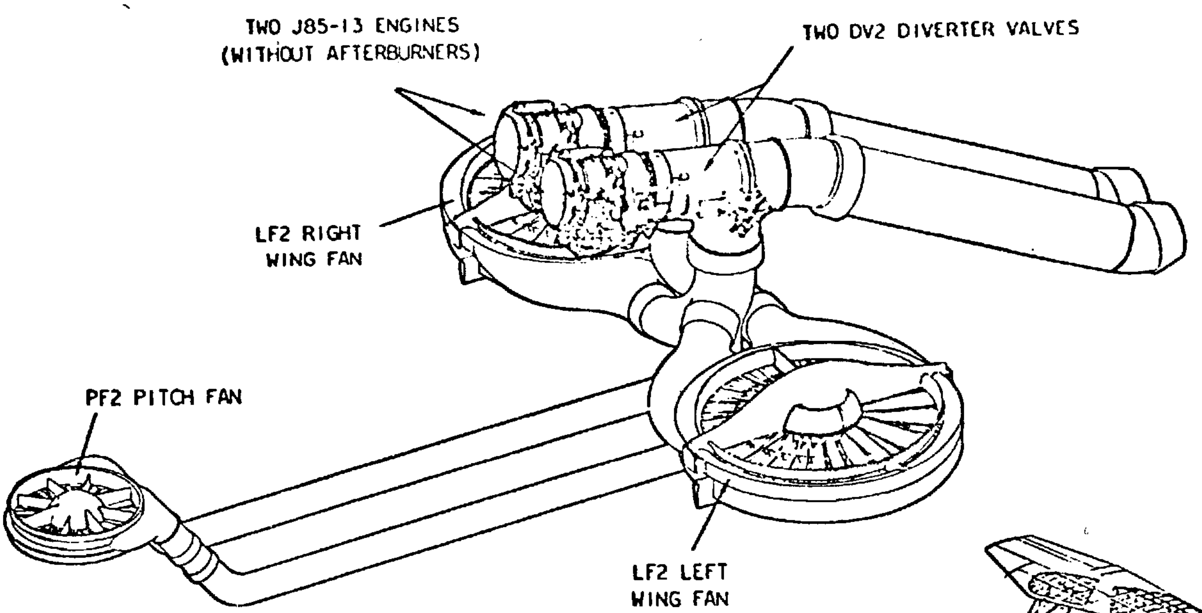

Figure 64. XV-5A Propulsion System

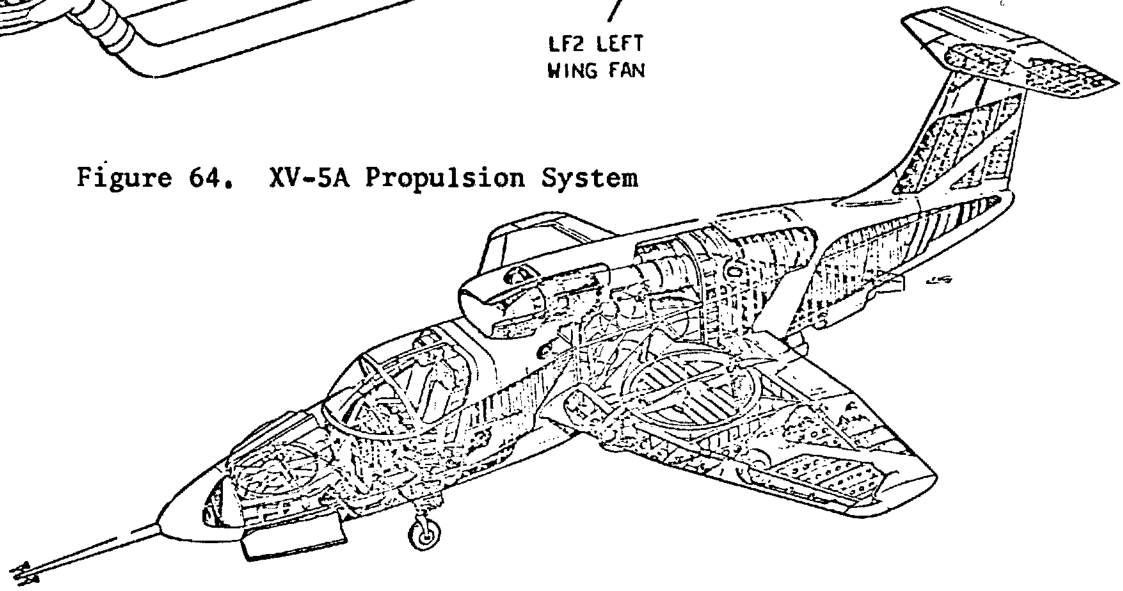

Figure 65. Integration of Propulsion System With Airframe

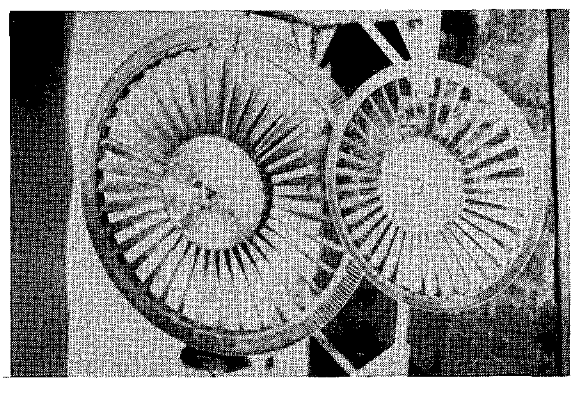

Figure 66. Wing Fan & Pitch Fan Rotors

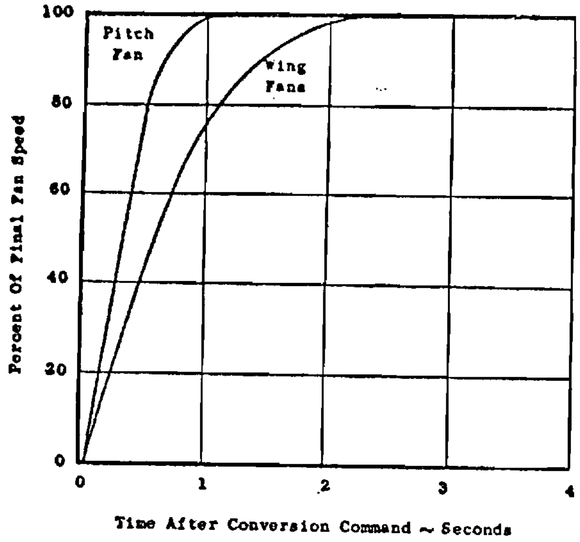

Figure 67. Fan Performance During Conversion

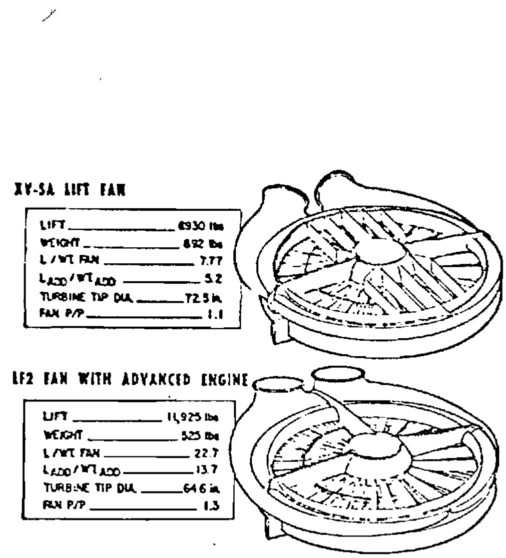

Figure 68. Lift Fans

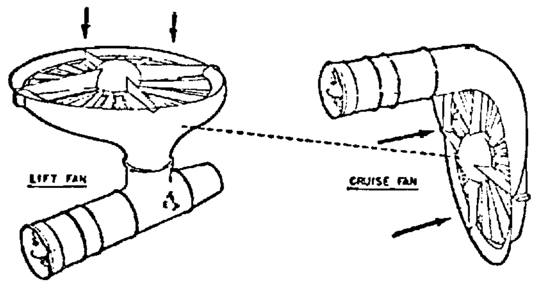

Figure 69. Evolution From Lift To Cruise

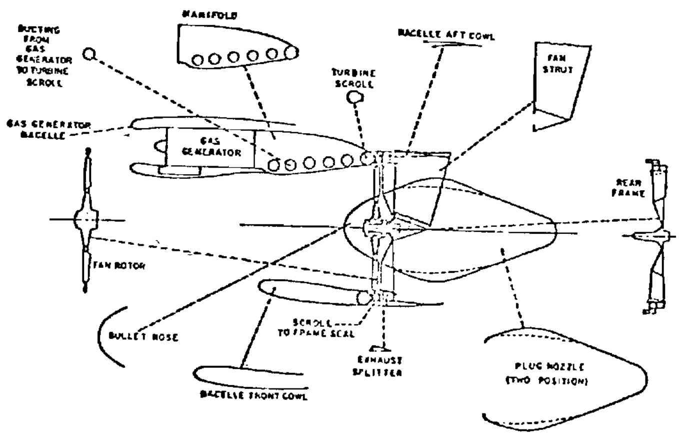

Figure 70. Lift/Cruise Fan Components

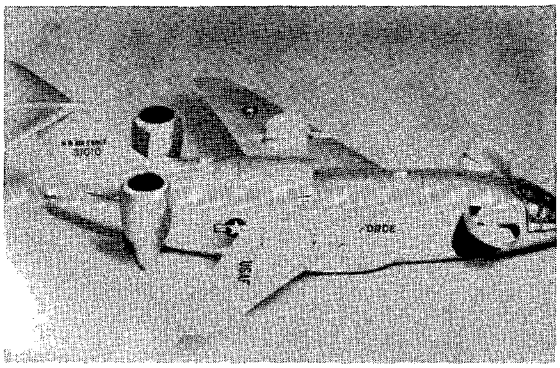

Figure 71. Lift Fan Powered Transport VTOL Mode

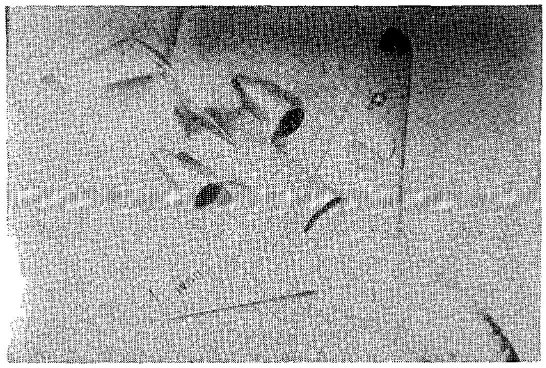

Figure 72. Lift Fan Powered Transport Cruise Position

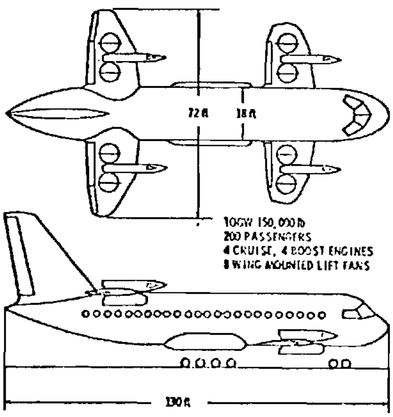

Figure 73. Short Haul V/STOL Airliner

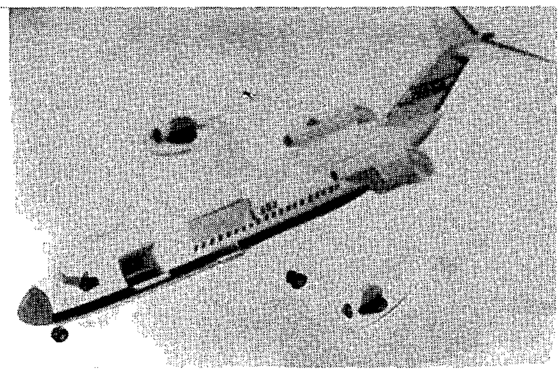

Figure 74. NASA STOL Transport Concept

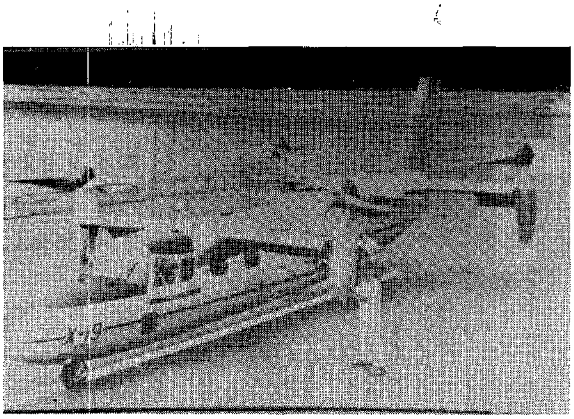

Figure 75. Curtiss-Wright X-19

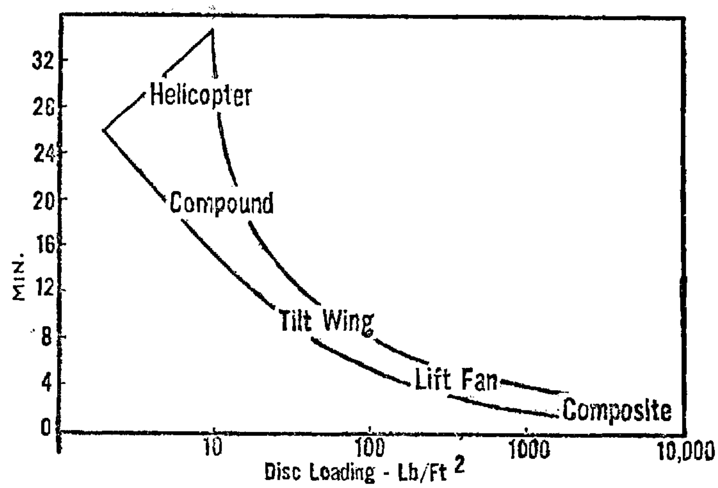

Figure 76. Time In Lift vs Disk Loading

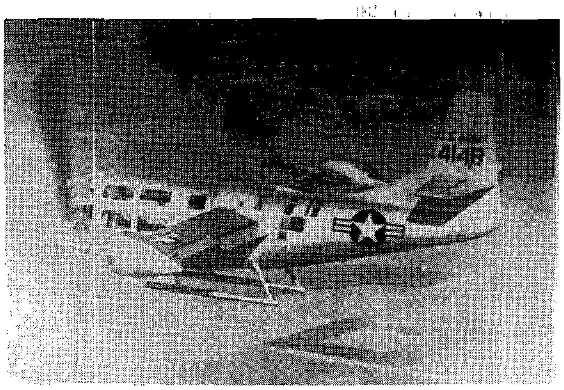

Figure 77. Bell XV-3

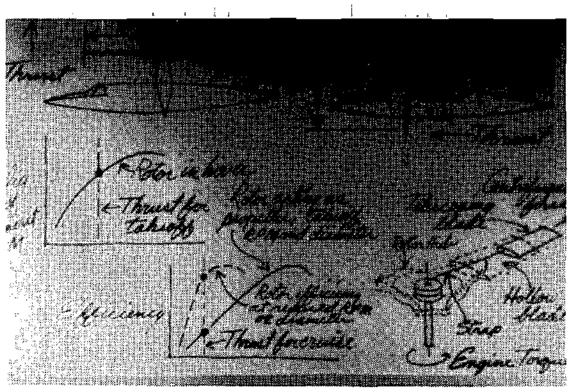

Figure 78. Variable Diameter Rotor

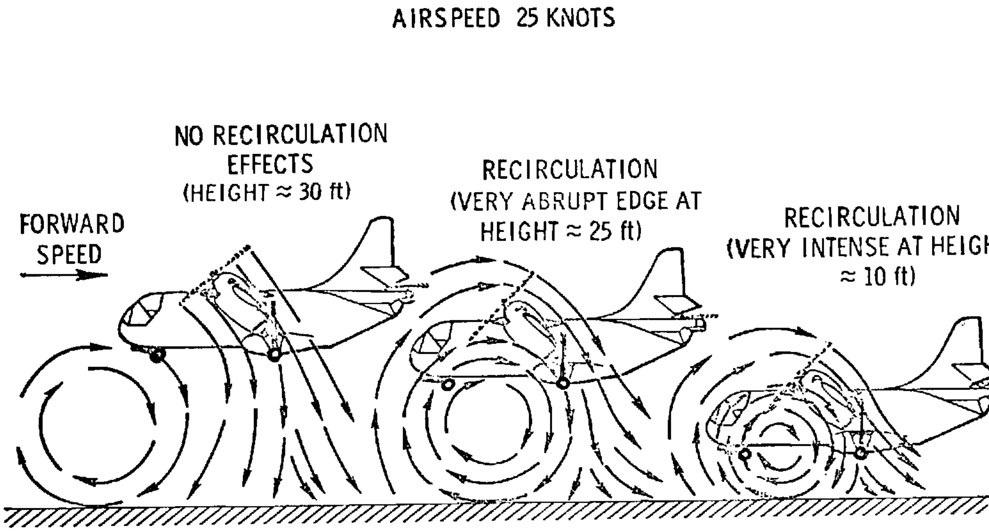

Figure 79. XC-142 Ground Recirculation Patterns

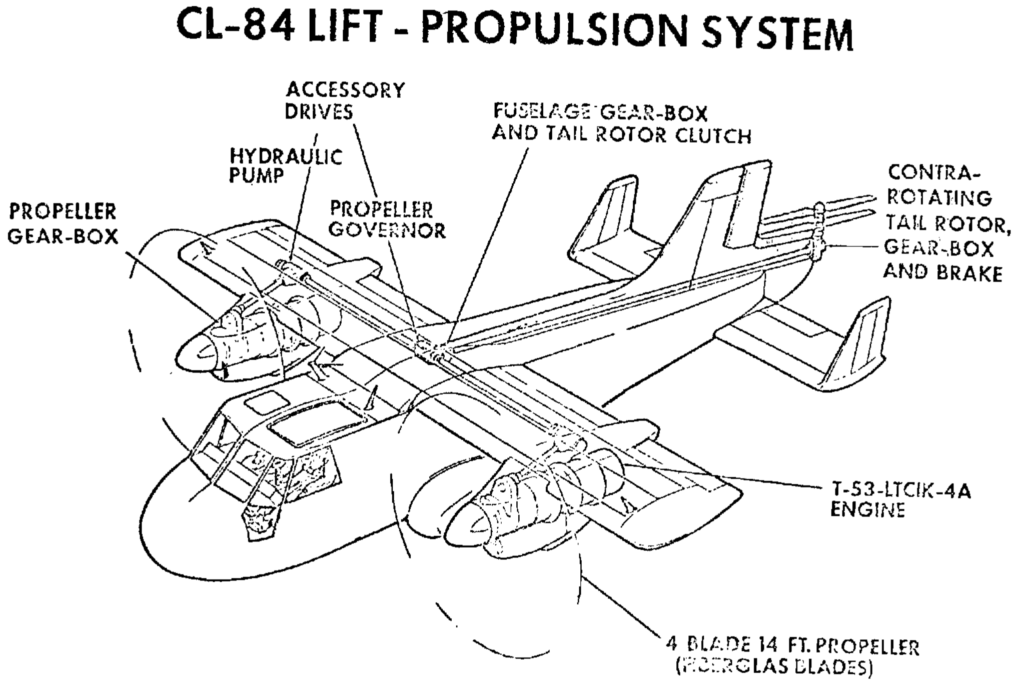

Figure 80. CL-84 Lift-Propulsion System

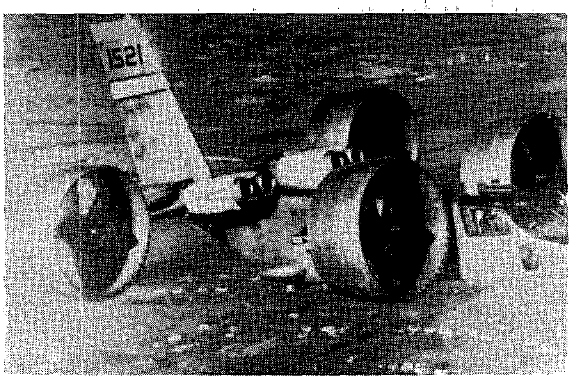

Figure 81. Bell Aerosystems X-22A

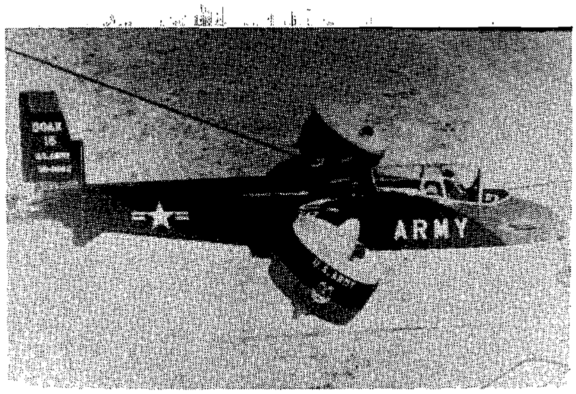

Figure 83. Doak 16

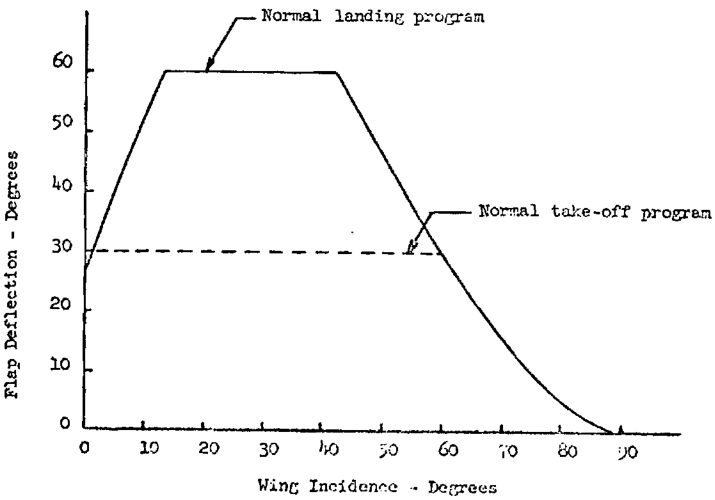

Figure 82. XC-142 Wing-Flap Program

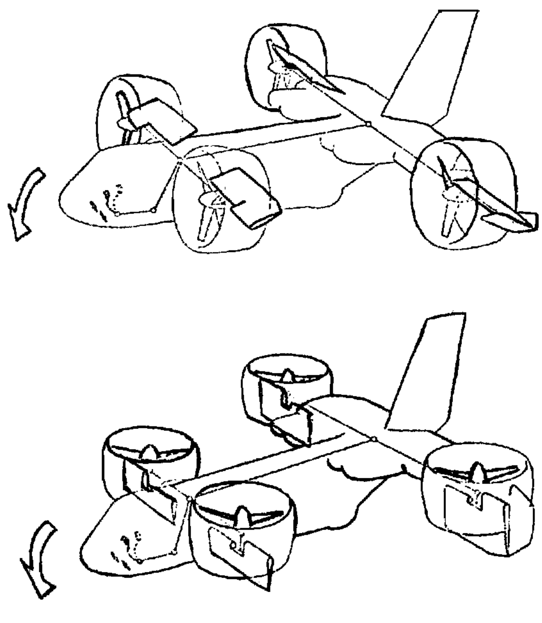

Figure 84. X-22A Pitch Control System

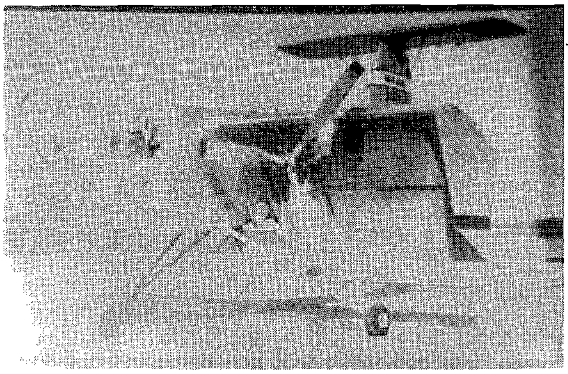

Figure 85. Ryan VZ-3

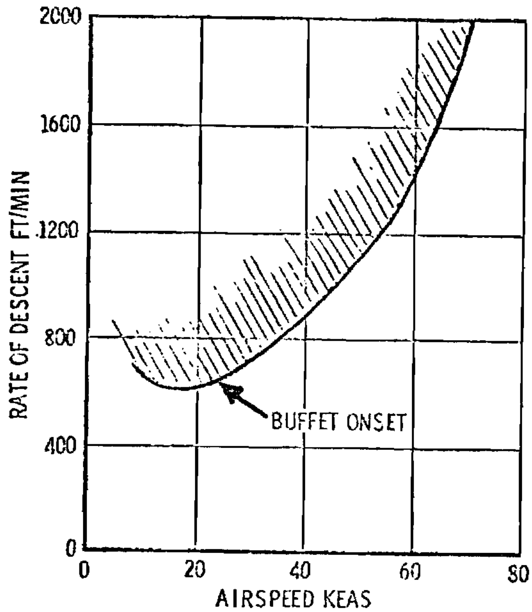

Figure 86. CL-84 Descent Performance

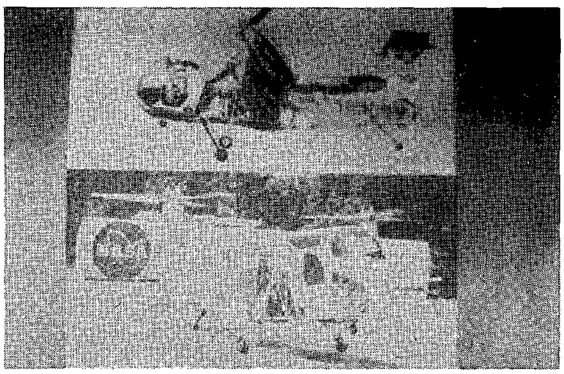

Figure 87. Vertol VZ-2

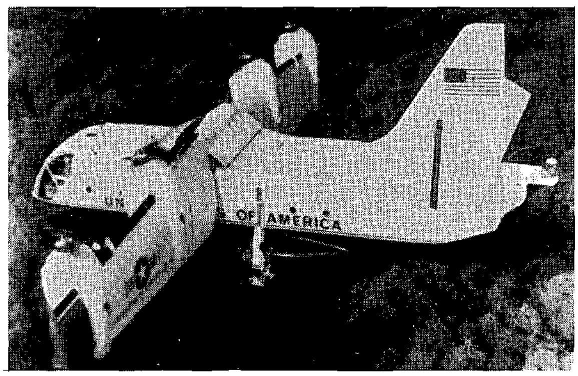

Figure 88. XC-142 In Take Off

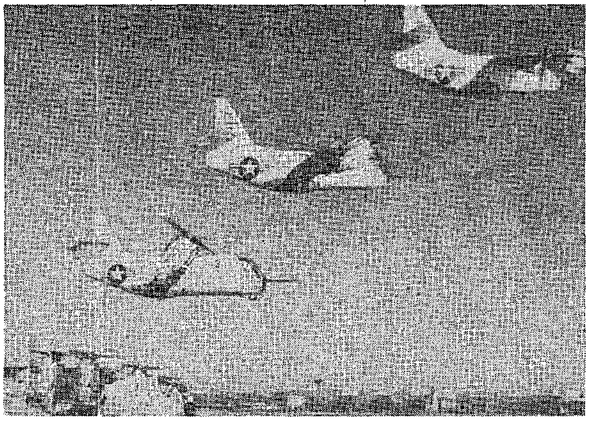

Figure 89. LTV-Hiller-Ryan XC-142A

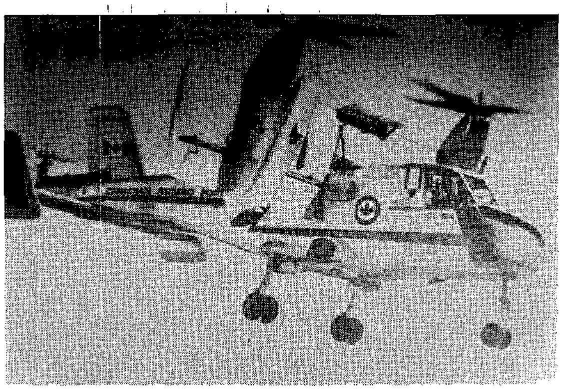

Figure 90. Canadair Limited CL-84

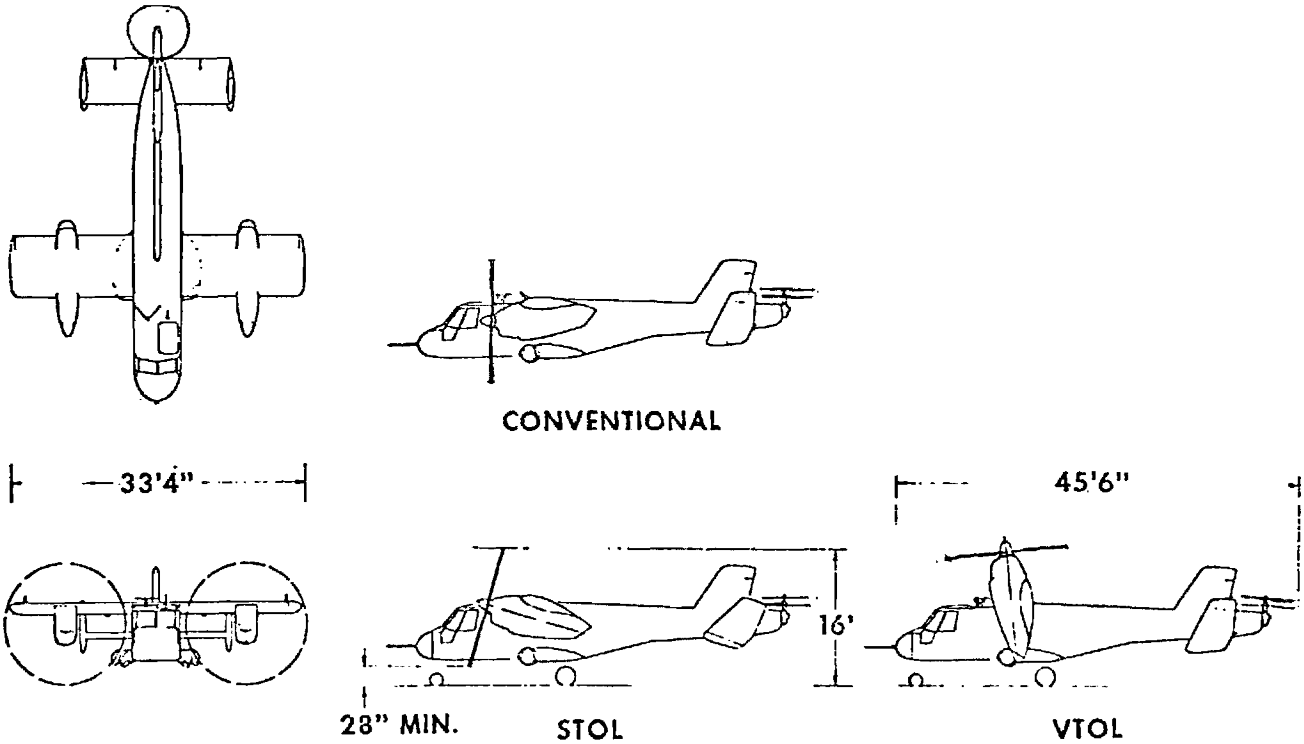

Figure 91. CL-84 General Arrangement

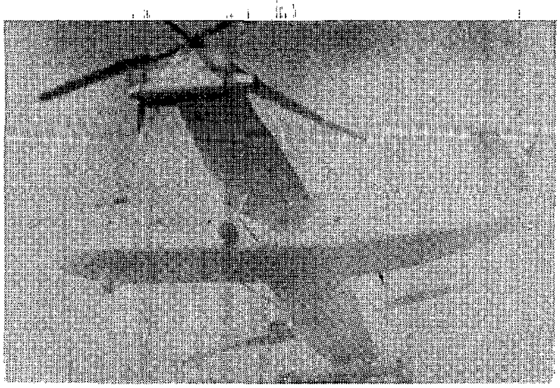

Figure 92. Russian Aircraft Sets World Speed Record

Figure 93. AH-56 Army Compound Helicopter

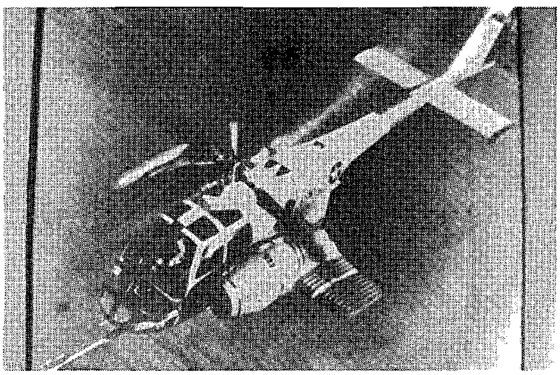

Figure 94. Lockheed XH-51

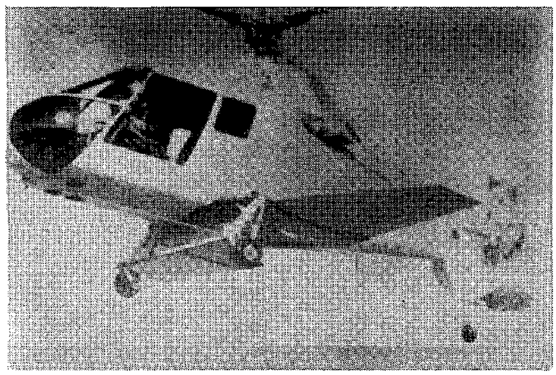

Figure 95. Paisecki Compound

Figure 96. Aircraft Gross Weight Of 231,000 Pounds

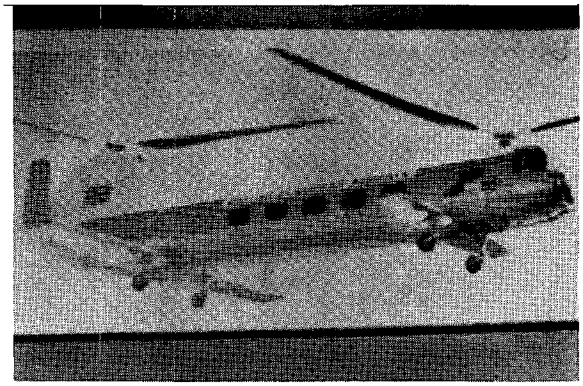

Figure 97. A Double Compound

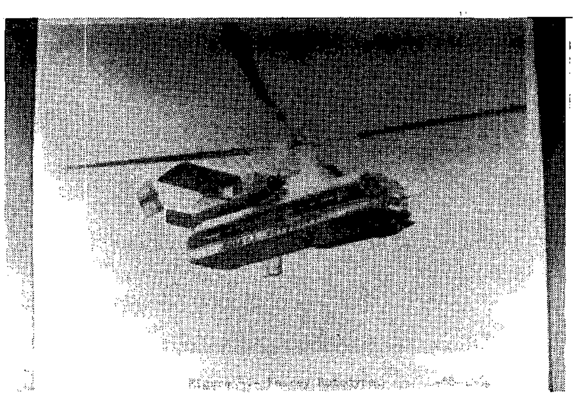

Figure 98. Air Bus

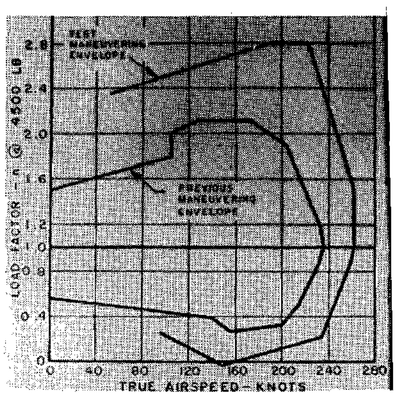

Figure 99. XH-51 Performance Envelope

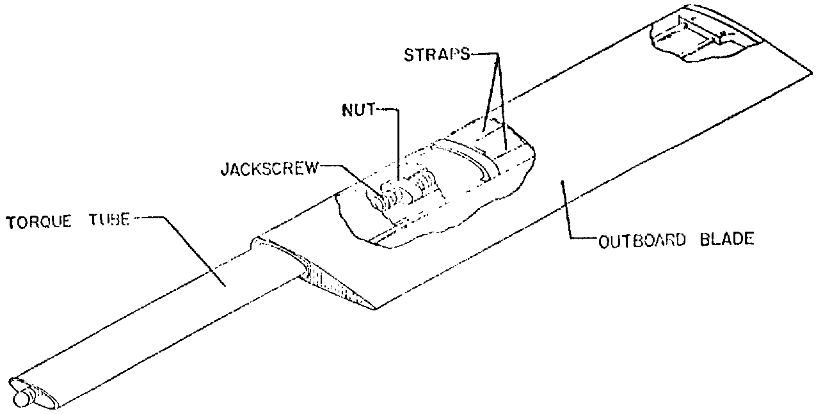

Figure 100. TRAC Blade Schematic

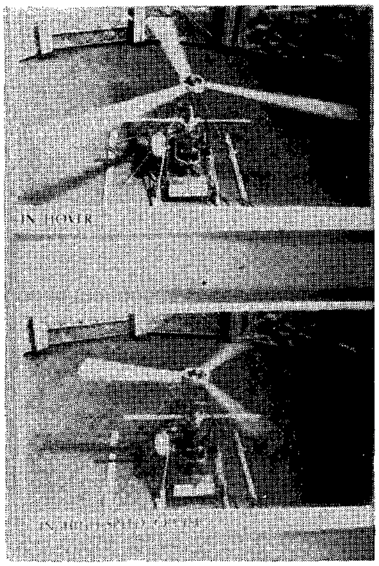

Figure 101. Bell Variable Diameter Rotor System

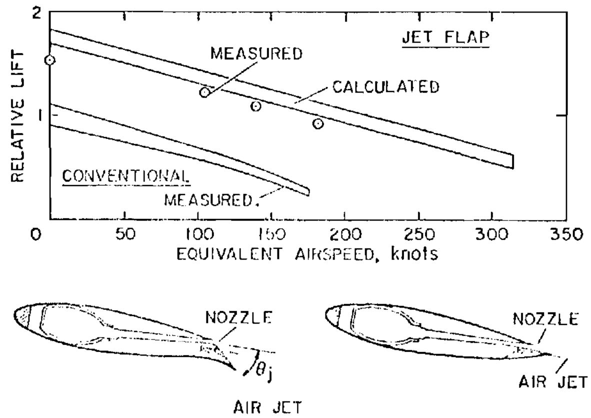

Figure 102. Jet Flap Rotor Performance

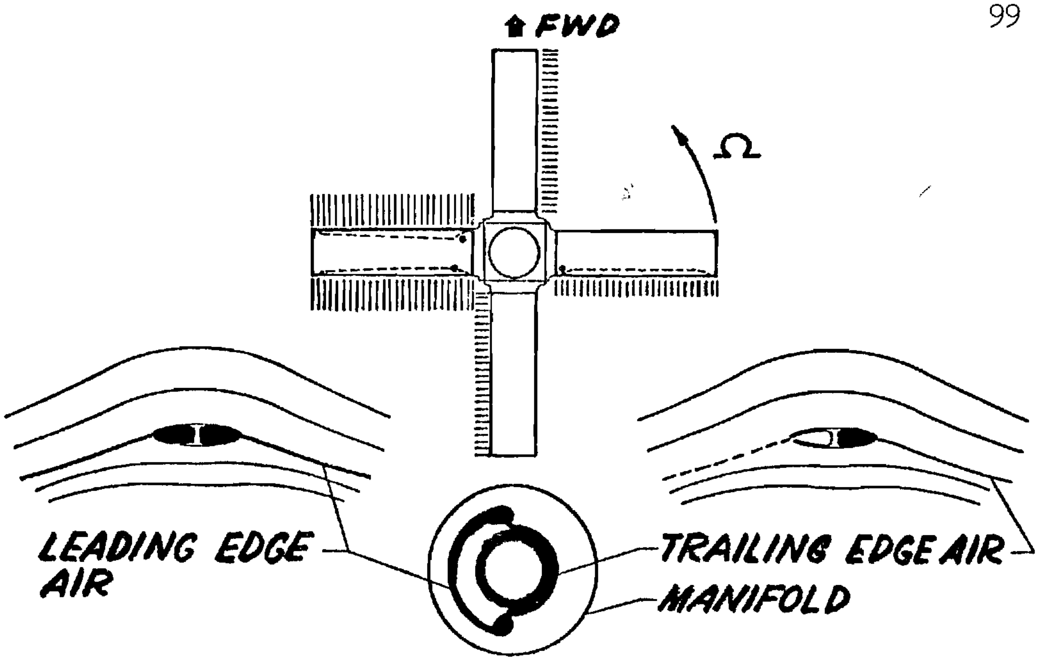

Figure 103. Jet Flap Rotor Concept

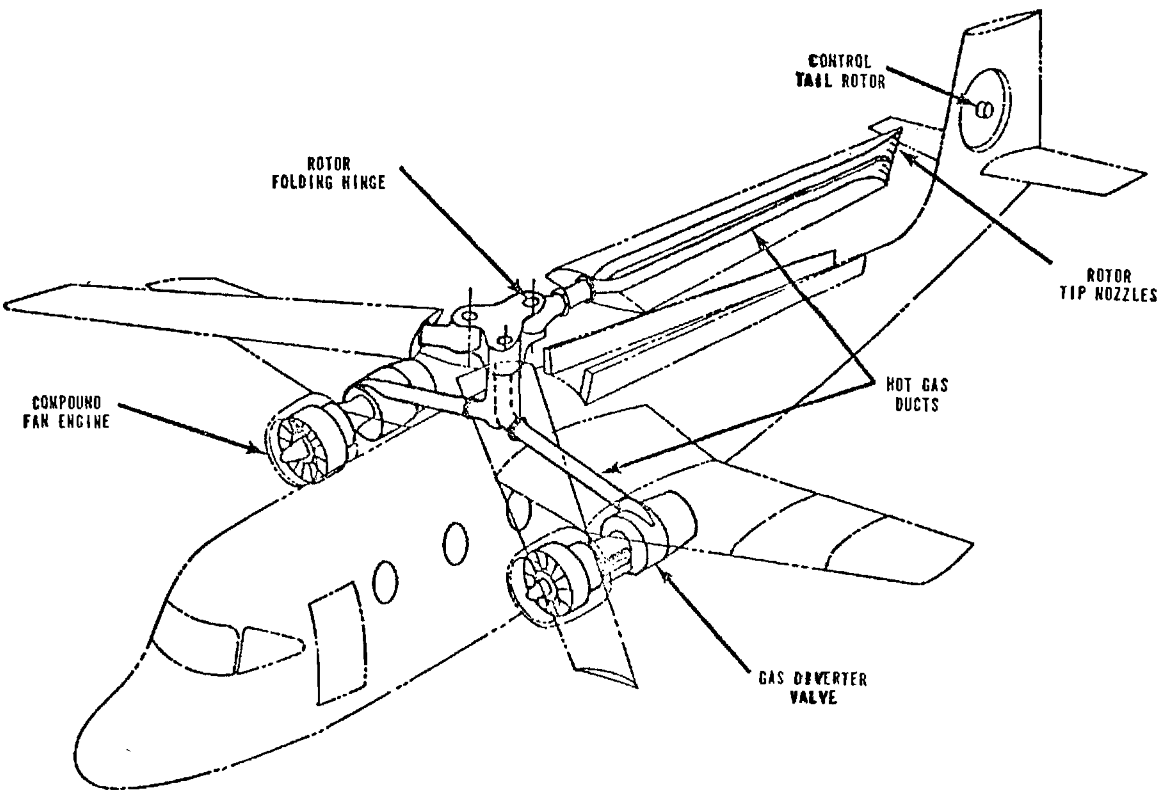

Figure 104. Convertiplane With Jet Tip Drive

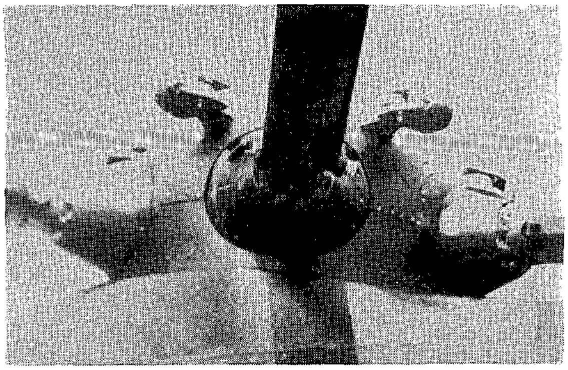

Figure 105. Bifilar Vibration Absorber Protrudes Above Rotor

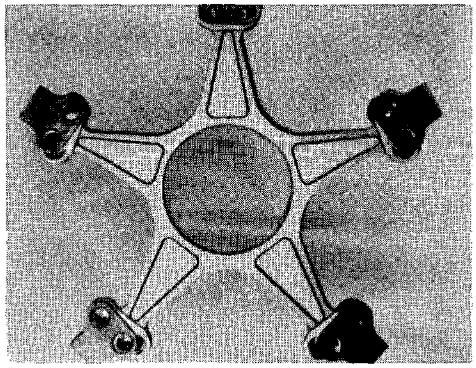

Figure 106. Bifilar Vibration Absorber

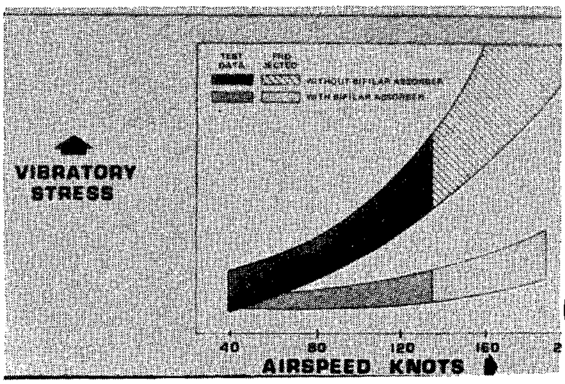

Figure 107. Airframe Stress Reduction

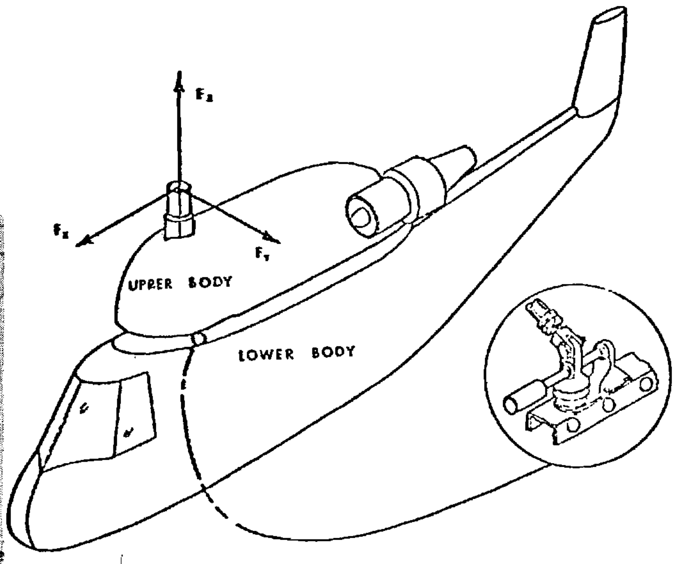

Figure 108. Diagram of Two-Body System

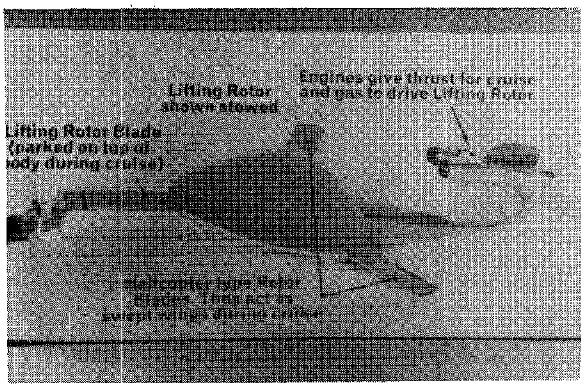

Figure 109. Hughes Stopped Rotor Concept

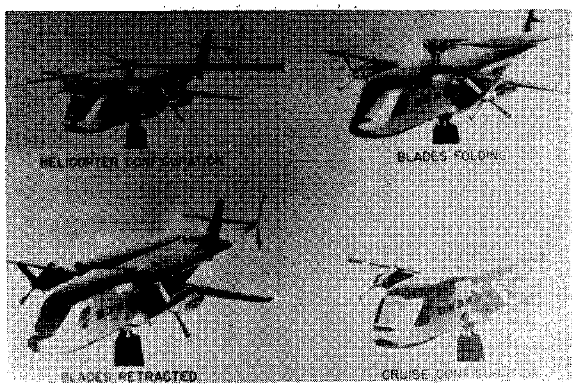

Figure 110. Stowed Rotor Concept

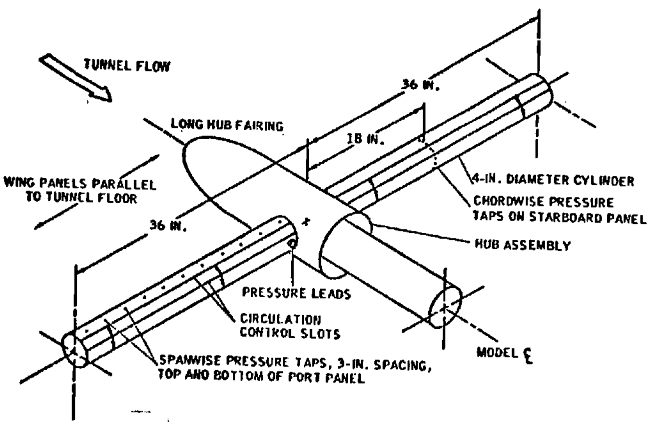

Figure 111. Spanwise Pressure Tap Location

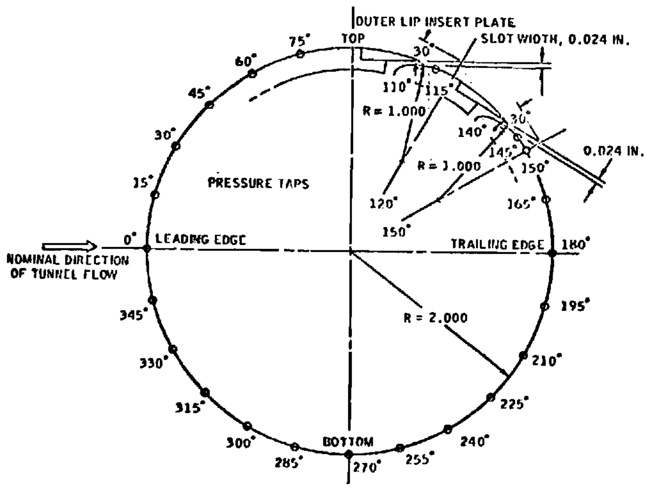

Figure 112. Slot Geometry and Pressure Tap Location

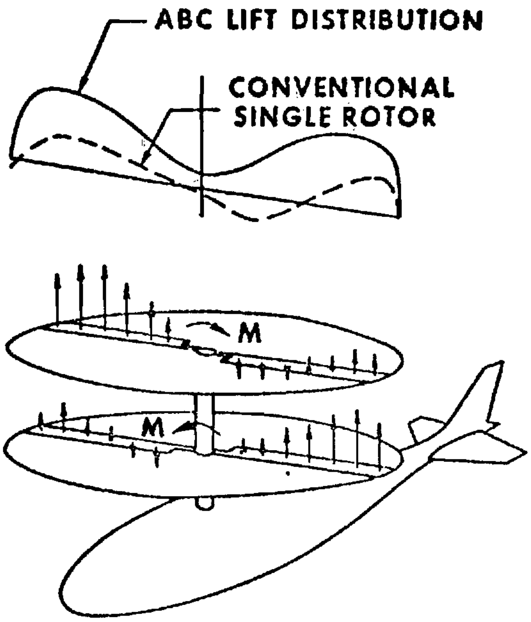

Figure 113. Advancing Blade Concept

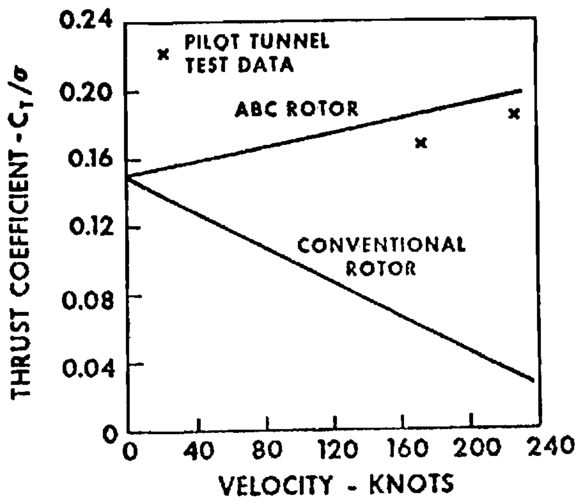

Figure 114. Maximum Thrust Coefficient

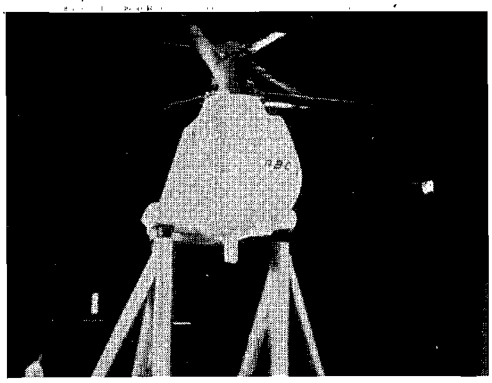

Figure 115. Full Scale ABC At Ames Test Center

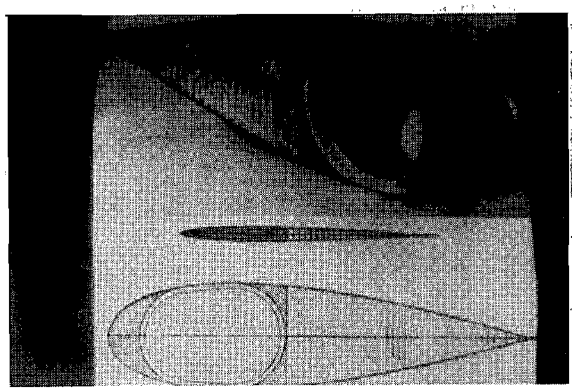

Figure 116. Titanium Technology Supports Stiff Blade

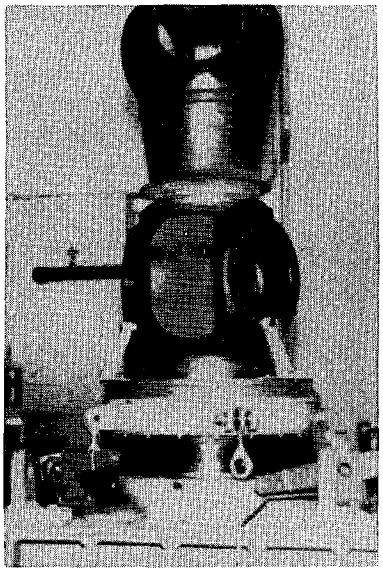

Figure 117. Advanced Design Hubs Support Large Moments

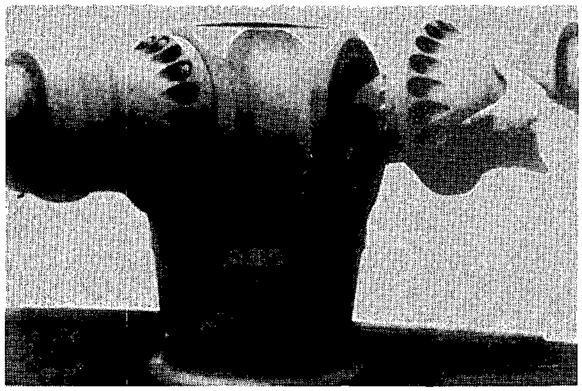

Figure 118. Blade Mechanics Are Greatly Simplified

Figure 119. Marchetti SV-20 Carries 20 Passengers

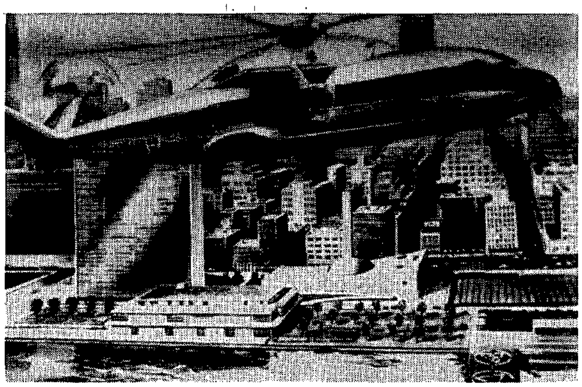

Figure 120. Sikorsky City Center Air Bus Carries 90 Passengers

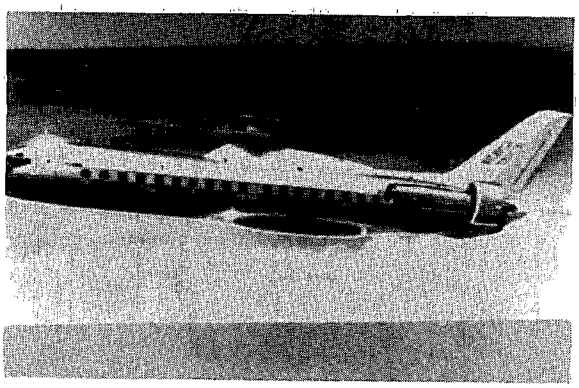

Figure 121. 500 Knot ABC Jetliner

	MANHATTAN TO PHILADELPHIA
ACCESS TO AIRPORT (JFK)	:45
TERMINAL TIME DISEMBARKING	:10
CHECK - IN	:20
TAXIING	:10
BLOCK TIME	:30
HOLDING TIME	:10
TAXIING	:10
TERMINAL TIME	
A/C TO GROUND TRANSPORT	:10
BAGGAGE CLAIM	:05
ACCESS TO CITY	:35
TOTAL TIME	3:05
AVERAGE SPEED (M.P.H.)	28 M.P.H.
TOTAL COST	$13.00

Figure 122. Representative Travel Times (727)

	MANHATTAN TO PHILADELPHIA
ACCESS TO TERMINAL	:15
TERMINAL TIME DISEMBARKING	:05
CHECK - IN	:10
ROAD TIME	2:00
TERMINAL TIME	
BUS TO LOCAL MODE	:05
BAGGAGE CLAIM	:05
TERMINAL TO DESTINATION	:10
TOTAL TIME	2:50
AVERAGE SPEED	31 M.P.H.
TOTAL COST	$5.00

Figure 123. Representative Travel Times (Bus)

	MANHATTAN TO PHILADELPHIA
ACCESS TO STOLPORT	:15
TERMINAL TIME DISEMBARKING	:05
CHECK-IN	:10
BLOCK TIME	:44
TERMINAL TIME	
A/C TO LOCAL MODE	:05
BAGGAGE CLAIM	:05
STOLPORT TO DESTINATION	:10
TOTAL TIME	1:34
AVERAGE SPEED	58 M.P.H.
TOTAL COST	$10.00

Figure 124. Representative Travel Times (STOL-Porter)

	CTOL	STOL
o TOTAL BLOCKTIME (WITH DELAY) (min)	83.8	39.5
o AVERAGE GATE TIME (min)	40	40
o ONE WAY CYCLE TIME (min)	123.8	79.5
o TRIPS/AIRCRAFT PER 12 hr DAY	5.82	9.05
o PASSENGERS/AIRCRAFT PER 12 hr DAY	699	1,087
o REQUIRED FLEET SIZE - NO. OF A/C	39	25
o PRODUCTIVITY/AIRCRAFT PER 12 hr DAY IN REV. PASS. MILES	131,200	204,000
o TOTAL UTILIZATION PER YEAR IN hrs PER AIRCRAFT	2,965	2,177
o PRODUCTIVE UTILIZATION PER YEAR IN hrs PER AIRCRAFT	1,020	1,512

Figure 125. Productivity & Utilization (New York-Boston: 10 Million One Way Fares Per Year)

DOLLAR/AIRCRAFT MILE	CTOL		STOL	
DELAY TIME	0	30	0	5
CREW	.74	1.15	.47	.54
FUEL & OIL	.32	.50	.49	.55
INSURANCE	.26	.34	.22	.31
MAINTENANCE:				
- AIRCRAFT LABOR	.16	.19	.18	.19
- AIRCRAFT MATERIALS	.22	.26	.27	.28
- ENGINE LABOR	.16	.22	.22	.24
- ENGINE MATERIALS	.21	.29	.46	.49
- MAINTENANCE BURDEN	.45	.58	.68	.72
DEPRECIATION	1.24	1.63	1.46	1.50
TOTAL DOLLAR/AIRCRAFT MILE	3.76	5.16	4.45	4.82
CENTS/AV. SEAT MILE	1.88	2.58	2.22	2.41

Figure 126. Direct Operating Costs (Boston-New York)

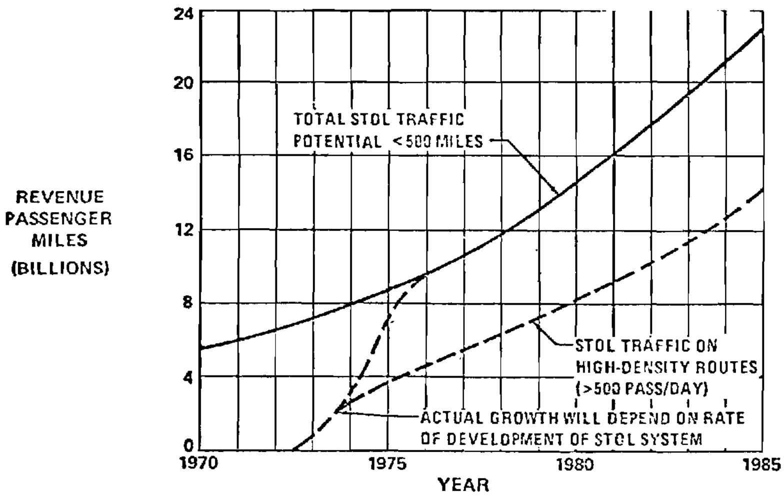

Figure 127. STOL Market Forecast (Continental US)

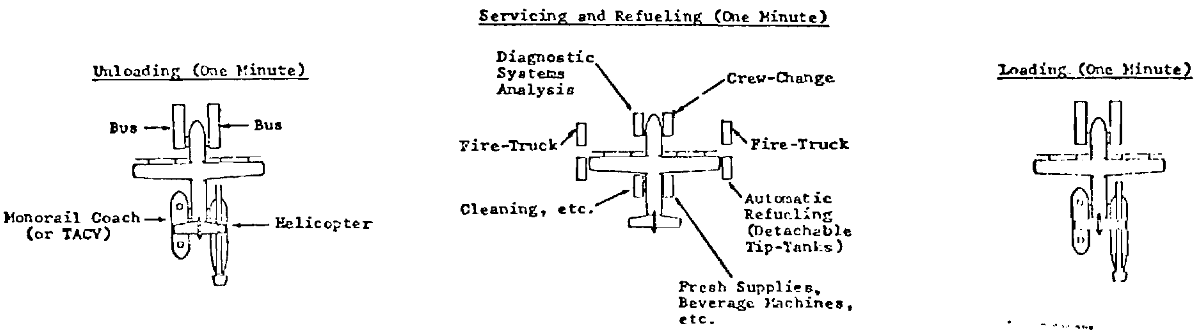

Figure 128. Metroport Turnaround Operations